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ELECTRICITY

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A
COURSE OF LECTURES
ON
ELECTRICITY

DELIVERED BEFORE THE SOCIETY OF ARTS

BY

GEORGE FORBES

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PREFACE.

In 1886 I was asked to give a course of lectures to the Society of Arts. Shorthand notes were taken of these lectures, and the first five lectures in the present volume are compiled from these notes, but with some alterations. The lectures were primarily intended for an intelligent audience, ignorant of electrical science, but anxious to obtain sufficient knowledge of the subject to be able to follow the progress now being made in the science. It is to such persons that the following pages may perhaps be useful. The sixth lecture is introduced with the object of showing the applications of the general principles to one department of practical engineering. It was originally delivered at the Electrical Exhibition at Philadelphia in 1884, at the request of the Franklin Institute.

In the course of these pages it has been my object to present in clear language the fundamental facts which govern electrical phenomena, and in such a manner as will leave the reader nothing to unlearn. To popularise the researches of our philosophers in a worthy manner is no easy task, and requires a special aptitude, and I have felt that to attempt such a work was a bold undertaking. Admirable works of this character on some of the sister sciences have already appeared; but in the science of electricity there has been a vacant space, which I have done my best to try to fill up. These lectures have no pretension to form an exhaustive treatise on electricity; but I trust they may be found to be a useful introduction to the study of this most fascinating science.

GEORGE FORBES.

34 GREAT GEORGE STREET, WESTMINSTER.

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ELEMENTARY LECTURES ON ELECTRICITY.

LECTURE I.

POTENTIAL AND ELECTROMOTIVE FORCE.

THE work of the philosopher studying the phenomena of nature is accomplished by the aid of either observation or experiment. In the science of astronomy we can only wait, watch and observe the signs which nature makes to us, and interpret the language in which she speaks. In the realm of electricity, on the other hand, we cannot depend much upon observation, and it is only in the laboratory by patient experiments that most of the secrets of electricity have been evoked. With the lightning flash, the aurora, and the direction of the compass-needle, almost the whole list of facts which can be learnt by observation in connection with electricity and magnetism has been completed, and it is by experiment in the laboratory that we must learn how varied are the phenomena, and how fruitful are the applications of this science, while at every step we find new pleasure in receiving the answers of experiments to our questions. The highest delight of the true philosopher is in seeking out new facts, and the chief charm in electricity to the true student is in grasp-

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ing the innumerable phenomena which are presented to his senses, and in co-ordinating and arranging these facts, until he finds that a few general laws govern all the diverse forms under which this protean agent manifests itself. It will be my object, in this course of lectures, to lay before you simply the fundamental phenomena and laws of this comparatively new but useful science, and to demonstrate experimentally the identity of the agent, however various may be the operations which it is called upon to perform.

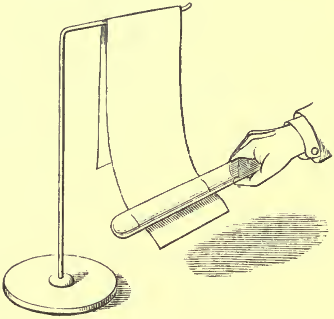

FIG. 1.—The suspended strip of silk after being rubbed with glass adheres to it.

The first electrical fact to be studied is the effect of rubbing together two bodies made of different material. After rubbing they show a tendency to adhere to each other. They are then said to be electrified. With some substances this is not easily made visible, but with others it is quite evident. Take, for example, silk and glass. I rub a dry glass rod with a strip of silk which is hung from a support above. After some friction when I try to withdraw the glass you see that the silk adheres to it. In frosty weather, when the hair of the head is dry, the friction of a comb often makes the hair cling to it in the same manner. The glass and silk lose the property after some time, but if the air be so dry that no moisture is condensed upon them they retain it for a long time.

Returning to the experiment, we may easily show something more. Withdraw the glass forcibly from the silk and the space between them acquires new powers. First, notice that when the glass is an inch or two from the silk and no sticking can occur, the action of the intervening electrified space causes the silk and the glass rod to approach each other. In the experiment as now arranged we can only show that the silk approaches the glass, but if we suspend the glass rod horizontally by its middle we see that the rubbed part of the rod moves to the silk. Of course you notice that for each of these experiments, I must first rub the silk and glass together.

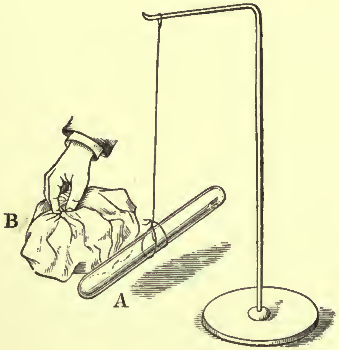

FIG. 2.

Silk B rubbed against end A of a glass rod. Rod then suspended in a stirrup by a thread, end A moves towards B.

But the space between the glass and silk has other properties. Here I have a light metal ball at one end of a stiff fibre of shellac which is hung by a thread at its middle. I rub a sheet of glass with silk. I hold the fibre of shellac in the hand, and cause the metal ball to touch the glass sheet. I leave the fibre to hang freely. I bring the silk and glass one on each side of the ball, and you see that the ball is acted upon by the space between the silk and glass so as to move from the glass towards the silk. After having touched the glass, the ball is acted upon by the electrified space in the same way as the glass was in the previous experiment (moving towards the silk). If, now, I first make it touch the silk and then hang it up, you see that the electrified space moves it towards the glass. In each case, contact with rubbed glass or silk causes the electrified space to act on the ball in the same way as it does on the material touched. We found before that the rubbed silk and glass are acted on by the space so as to move in opposite directions. We now find that after the light ball has touched the rubbed silk or glass the electrified space moves it also in opposite directions. In each case the ball is said to be electrified by contact, but there is something different in the two means of electrifying the ball. We must denote this by some language, so we say that the ball is positively electrified if it moves towards the silk, and negatively if it moves towards the

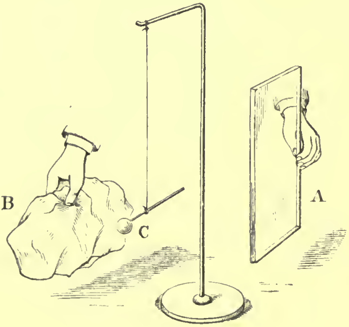

FIG. 3.

A. Sheet of glass. B. Silk rubber. C. Light metal ball on stiff fibre of shellac, suspended by a thread. If C has previously touched A it moves from A towards B. If it has touched B it moves from B towards A.

glass. It follows from this that, after the glass and silk have been rubbed, the glass is positively and the silk negatively electrified. We have now learnt that when an electrified body touches another which is not electrified, it takes some of the electrical condition from that other body.

If I have two metal balls on shellac fibres and touch the rubbed silk with one and the rubbed glass with the other, the one is said to be positively and the other negatively electrified. If the two are now made to touch, each is as much influenced by positive as by negative electrification. Thus both become neutral. (It will be understood presently that if the balls were not both conductors contact at every electrified part would be necessary to destroy the electrified condition.)

These actions of the space on an electrified ball and on rubbed glass and silk are the same as if two positively electrified bodies repel each other, and as if two negatively electrified bodies repel each other, and as if a positively electrified body attracts a negatively electrified body. Hence a rule is often given which saves time in stating the facts, namely, that 'like electricities repel, unlike electricities attract.' This is a most unscientific way of speaking, because there are no such things as electricities. Electricity is merely the science of electrical phenomena. Nor is it even true that the electrified bodies attract and repel each other. It is the electrified space which acts on the electrified bodies and makes them act as if they attract and repel each other. All this must be remembered if the above rule is quoted.

I have used a rod or sheet of glass and a strip of silk in these experiments; other materials would act similarly, though not always with the same intensity. Sealing-wax might be rubbed on flannel or cat's fur and the same effects would be observed. The rubbed sealing-wax if suspended in a paper stirrup between the mutually rubbed silk and glass would move from the silk towards the glass. Hence it is negatively electrified. The cat's fur or flannel is positively electrified. The most extensive experiments have all gone to prove that we cannot electrify one body positively without at the same time electrifying another negatively to an equal extent. In fact the only effects which we have observed or can discover are those produced in and by the electrified space lying between those bodies which we say are positively and negatively electrified.

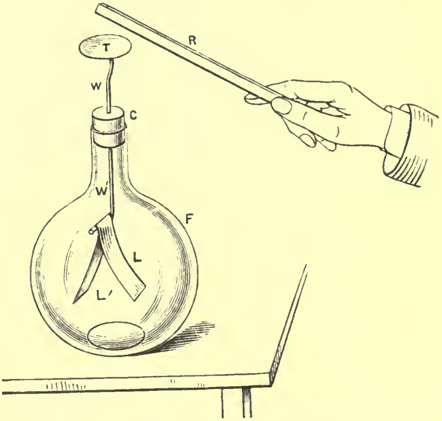

FIG. 4.—Gold-leaf Electroscope.

F. Glass jar. W. Metal rod. T. Metal disc. LL'. Gold leaves. When T is electrified, L and L' diverge, and take up the position of the dotted lines.

(When I speak of the space *between* two bodies I mean the space separating them, not necessarily in a straight line between them.) When I electrify one body by contact with an electrified one, what is given to the one is taken from the other.

I will now show you two instruments used for detecting feeble electrification. The first is the gold-leaf electroscope. A rod of metal has a metal knob or flat disc at the top, and two strips of gold-leaf facing each other at the bottom, and it is passed through the stopper of a jar at its middle. The gold-leaves are very light and the jar prevents currents of air from blowing them about. I touch the disc with a positively electrified body. The two leaves L and L′ become positively electrified. There must of course be a negatively electrified body somewhere. Call it F. The space which separates the leaf L from F includes the positively electrified gold-leaf L′. Hence L′ moves from L and towards F. So also the space separating the other leaf L′ from F is electrified and acts on L. Thus L and L′ are caused to diverge when an electrified body touches the disc. You see this when I rub a piece of glass with silk and touch the disc with it. There now, the leaves diverge.

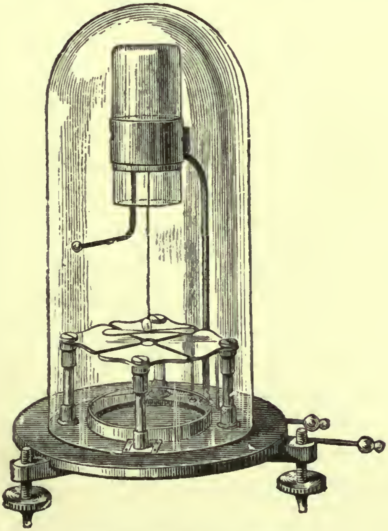

FIG. 5.—Quadrant Electrometer.

The other instrument for detecting feeble electrification is the quadrant electrometer. I will not now describe the beautiful complete instrument, but will merely show a simple form which illustrates the principle of the instrument. Here I have a horizontal metal circle cut into four quadrants, A B C D, by two diameters. The metal quadrants are supported on glass stems. I rub some glass and silk together. I touch two opposite quadrants A and C with the glass and the other two, B and D, with the silk. The two former are now electrified positively, the two latter negatively. The condition of the electrified space near to the quadrants is such that a positively electrified body tends to go from A and C towards B and D. I now hang a metal index horizontally by a silk fibre over the intervals separating A and B, and C and D. If now the index is even feebly electrified the electrified space in which it lies will move it either towards A and C or towards B and D according as it is negative or positive. My instrument is made still more sensitive by having a light mirror attached to the index and reflecting a beam of light from a lamp on to a scale. The slightest motion of the index is shown by a movement of the spot of light. I have also a wire hanging from the index and dipping into a glass dish containing liquid. This enables me to electrify the index without shaking it.

I will now use this delicate instrument to show you an experiment. I have a piece of zinc and a piece of copper, each fastened to a rod of glass. I bring the brass and zinc quite lightly into contact for a moment. Are they electrified? Let us try and see. I touch the liquid with the zinc. The spot of light moves several inches to the right, showing that the index has moved from A and C towards B and D. I now know that mere contact of zinc and copper electrifies the zinc positively, and of course the copper must be negative. This is seen now by a motion of the spot of light to the left. This is a very feeble force compared with what glass and silk give us. In scientific language, the difference of electrical potential of rubbed glass and silk is tens of thousands of times greater than that of zinc and copper when lightly touched. But this last difference of potentials which gave us a motion of about two inches of the spot of light is almost exactly what we take as our unit and call *a volt.*

But I am anticipating. To return to this electrometer, I might show you by its aid that any two dissimilar substances when rubbed or even pressed together are electrified, the one positively and the other negatively. If any two of the following substances be rubbed together, the one first on the list becomes positively, the other negatively, electrified.

POSITIVE.

Cat's fur.
Polished glass.
Wool.
Cork, at ordinary temperature.
Coarse brown paper.
Cork (heated).
White silk.
Black silk.
Shellac.
Rough glass.

NEGATIVE.

I wish you to notice that the order of the objects in such a list does not depend merely upon the material but also on the nature of the surface. In the table you see that rough glass is put at the bottom and polished glass near the top. Hitherto in our experiments with glass it has been smooth. Here I have a rod of glass with one end rough, the other smooth. I rub the polished end and touch the disc of the gold-leaf electroscope which is now positive, and the leaves diverge. On approaching the rubbed glass to the disc of the electroscope, you see that the leaves diverge farther. I now rub the rough end of the glass rod. I bring it near the electroscope, the leaves converge showing the opposite kind of electrification. This difference depends upon the mechanical nature of the surface. We find that the surface has an influence on the character of the electrification. Thus also we find that a black ribbon rubbed with a white one is negative to it. We find that a hot piece of cork rubbed against a cold one is negative to it. I would remark that in all these cases of surface influence the best radiator of heat or light is the most negative. A hot body radiates more heat than a cold one, and is negative to it. A rough surface radiates more than a smooth one, and is negative to it. A black body radiates more heat than a white one, and is negative to it. I give this only as an aid to memory. I do not imply that there is a physical connection between the two phenomena, although there are some startling similarities in some of the actions of bodies in relation to heat and electricity.

Hitherto I have dealt chiefly with the electrification of materials which we call insulators, and which do not conduct the electrical condition easily. If I rub a piece of brass with cat's fur you see that it has no influence whatever upon the electroscope; but this is not because the electrical condition is not created. The reason is that brass is able to conduct the electrical condition which it acquires through my hand and body to the ground and so over the surface of the earth. If I put this handle of shellac to the brass rod, the shellac acting as an insulator does not allow the electrical condition to pass to my hand. I rub the brass and you now see its influence on the electroscope.

I can show this in another way; by striking the brass disc of the electroscope with a piece of silk, you see that the gold leaves are caused to diverge.

In the experiments with the quadrant electrometer you may have noticed that I used glass supports on several occasions. I put the metal quadrants on glass stems, I put the liquid into a glass dish, and I put glass rods for handles on the zinc and copper discs. The reason of this is that glass does not allow the electrical condition to pass along it. You have seen that the electrical condition can leave one body and go to another, when it is of metal, merely by contact. You might naturally suppose that the electrical condition of the brass quadrants would spread all over the table and floor. It would do so if the quadrants were not separated from the table by a substance such as glass which is said to be an insulator and prevents this action. The silk fibre supporting the index is also an insulator. The shellac fibre used in another experiment is an insulator. Most fortunately for the philosopher our atmosphere is an insulator. Otherwise all the experiments you have seen would fail. If the air were not an insulator but a good conductor of the electrical condition, it is probable that we should know absolutely nothing of the existence of this wonderful agency electricity. It is only in empty space or in space filled with insulating matter that we discover the electrical condition which we are now studying. The following table classifies some substances as good insulators and good conductors, and the more general class of bodies which are both imperfect conductors and imperfect insulators.

GOOD CONDUCTORS.—All the metals and carbon.

BAD CONDUCTORS AND BAD INSULATORS.—Common water, aqueous solutions, moist bodies, besides wood, cotton, hemp, &c., in any except a very dry atmosphere, liquid acids, rarefied gases.

GOOD INSULATORS.—Paraffin (solid or liquid), turpentine, silk, sealing-wax, india-rubber, gutta-percha, dry glass or porcelain, mica, air at ordinary pressures.

[It may be noticed that the best electrical conductors are also the best thermal conductors. Also that a red-hot temperature converts insulators into fairly good conductors.]

In any atmosphere except a very dry one many materials, pre-eminently glass, condense an invisible film of moisture on their surfaces which then become imperfect insulators. For this reason in a moist climate many experiments succeed best if the apparatus is kept warmer than the air of the room. This prevents the condensation of moisture on its surface.

The quantity of electrification which we can obtain by rubbing a rod of sealing-wax or glass is very trifling, and when we wish to obtain powerful effects we must use large surfaces. Electrical machines have been much used in which motion round an axis is given to a piece of glass, sulphur, or ebonite, having a very large surface which is rubbed by a fixed rubber often made of silk smeared with an amalgam of mercury. Some such machines have been made with discs of glass seven feet in diameter.

The power wasted in friction is considerable, and the atmosphere must be dry for success with this machine. Of late years a more convenient class of machine has been invented, as a special example of which I may mention the well-known influence-machine of Mr. Wimshurst, which I shall be using immediately. Here I have a large and very powerful multiple plate machine most kindly constructed, specially to illustrate this lecture, by Mr. Wimshurst, who has spent a great deal of time in improving the construction of machines for generating intense electrification. In this machine there are two brass knobs or conductors which are joined metallically to the collectors. One knob collects positive, and the other negative electrification on its surface. The machine gets up intense power with a few turns of the handle in any state of the atmosphere, however moist. These knobs enable us by contact to obtain very great differences of potential on very large surfaces.

This term 'difference of potential' is a term we often apply to electrified bodies, but it requires explanation. A positively electrified body is said to have a higher electric potential than the Earth whose electric potential is zero. The Earth again has a higher potential than a negatively electrified body. We also say that when zinc or copper are touched they have a difference of electric potential. When an electric current goes through a wire we say that different parts of the wire have different electric potentials. When those powerful generators of electricity called dynamo-machines are at work we often speak of the difference of potential at the terminals, or at the brushes. The expression will be so often used in describing electrical phenomena that I will now say a few words about it. It is a comparatively new expression in scientific language, but one of

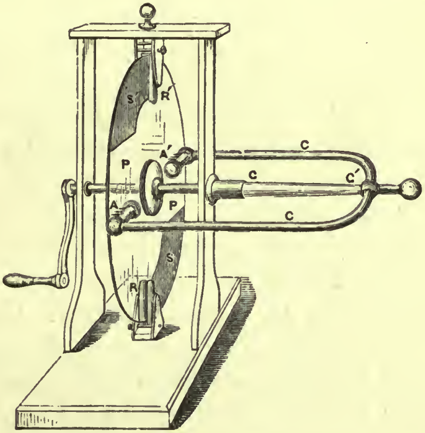

FIG. 6.—Friction Electrical Machine.

P. Glass disc. R. Rubber. A. Metal points to carry off the electrical condition. C. The knob, or prime conductor, which becomes positively electrified when the handle is touched.

great importance. We know that the force of gravity gives velocity to a falling body, and the body acquires energy of motion—*kinetic* energy it has been called. But when a body is raised from the floor to the table it acquires energy of position, not of motion, because it has the power of falling to the floor and so doing a certain amount of mechanical work. How are we to define the energy which exists in a ball when placed on a table. It has a potency of doing work. It has what Rankine called potential energy, and the word expresses very well what we mean. Suppose a ball to be thrown up in the air. At starting it has kinetic energy, energy of motion, which gradually diminishes and disappears, giving place to energy of position at the top of the ball's flight when the ball has no motion. The great principle of the conservation of energy tells us that at each part of the ball's flight the sum of these two energies remains the same (neglecting the slight dissipation of energy by friction with the air). You understand then what we mean by potential energy. The difference of gravity potential between the floor and the table is measured by the energy given off by a unit mass falling from the table to the floor, or by the work that is done in raising a unit mass from the floor to the table.

If now I have a piece of glass positively, and a piece of silk negatively, electrified, some work must be done in moving a body with a unit charge of positive electrification from the silk to the glass. This measures the difference of electric potential between the glass and silk. This definition involves a further definition of the unit charge, but we are not far enough advanced in our studies for me to define what we use as a unit charge. The quadrant electrometer which you have seen me use measures differences of electrical potential by the motion of the spot of light. The most sensitive instrument for this purpose is the quadrant electrometer of Sir William Thomson.

Hitherto I have been speaking to you about electric forces, which we can thoroughly understand as being forces because we see their effect in the motion of material bodies. I am now going to describe a kind of force which does not rightly have that title in the Newtonian sense of the word. It is usually called electromotive force, implying that it is a force which moves electricity and not matter, and since electricity is not a material substance this is not strictly a force. Newton called force that which causes or tends to cause motion in a body. While we have been watching the electric forces we have seen motions given to a piece of matter. When the force of gravity is acting on a falling body it is producing motion, when it is acting on a weight on a table it is *tending* to produce motion, but it only exerts pressure on the table owing to the resistance offered by the table. In all cases of force-action, as Newton intended the word force to be used, there is motion produced

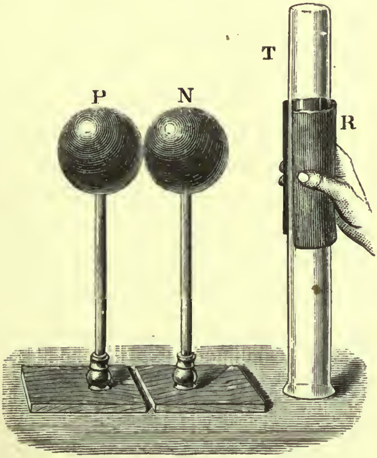

FIG. 7.—Glass balls and rod.

P and N. Two balls in contact, but on insulating glass stands. T. Glass cylinder rubbed with silk and positively (+) electrified. N becomes negative and P positive.

or a tendency to produce motion in a piece of matter. Electromotive force moves, or tends to move, a positive electrification in one direction and a negative electrification in the opposite direction in a conductor; this rearrangement of the electrification is called *electric induction*. I will now show you the action of an electromotive force upon a conductor. Here I have two large metal balls in contact, but each on an insulating stand of glass. Neither ball is electrified. Now I take a glass cylinder and rub it with silk. It is now positively electrified. I touch the gold-leaf electroscope with the electrified cylinder and the leaves diverge with positive electrification. I now place the electrified glass cylinder close to one of the balls, but not touching. Now the cylinder produces an electromotive force, attracting as it were negative electrification to the nearest ball and repelling positive to the farther one. I take away the farthest ball and bring it near the disc of the gold-leaf electroscope. The leaves diverge further, showing positive electrification. I now bring the other ball near it and the leaves collapse. The two balls have been electrified by induction, one positively, the other negatively.

Thus we see that not only can an electrified body produce a visible effect in the way of motion on a material body, but it is also able to attract and repel the electrical condition in a conductor. If the electrified cylinder have no conductor near it, but only air, which is an insulator, it cannot produce this induction, but can only produce a pressure or strain on the insulating medium due to the tendency to produce induction. The medium offers resistance to the electromotive force just as a table offers resistance to the fall by gravity of a weight. Putting the metal balls in the strained space relieves the strain and they suffer induction.

I will now show you one or two of the applications of this principle of induction. The first illustration is with the gold-leaf electroscope. I rub my glass rod with silk. I bring it near the disc of the electroscope. The leaves diverge. The rod is positive. It attracts negative to the disc and repels positive to the gold leaves and causes them to diverge. I remove the glass rod. Induction ceases. The leaves collapse.

I now repeat the experiment in another way. Holding the rubbed glass as before near to the disc of the electroscope I touch the latter with my finger. The repelled positive condition passes through my body to the ground. The gold leaves are now negatively electrified and stand apart. I remove my finger and then the glass rod and the leaves remain apart being negatively electrified.

It is due to this induction that the ordinary electrical attractions are seen. I have a pith ball suspended by a silk fibre. I bring a piece of rubbed glass near. Positive electrification goes to the side of the ball farthest from the glass rod, and negative to the near side. The attraction in the near side is greater than the repulsion on the far side owing to the difference of distance. Thus you see the pith ball is attracted. When the pith ball touches the glass rod, it is electrified by contact positively and is repelled. I have a piece of gilt paper bent into a circle with its ends joined, I lay it on the table over which you see it rolling in following the glass rod. Here also induction is first set up resulting in attraction. I tear up some small scraps of paper and lay them on the table. I rub a piece of sealing-wax on my coat-sleeve and bring it near the paper scraps. Induction sets in and they are lifted off the table and fly to the sealing-wax. They do not fall from the sealing-wax by repulsion because the fine fibres at the edge of the paper are pretty good insulators and prevent the electrical condition of the sealing-wax from passing to the paper.

There are innumerable applications of this principle of induction. Here I have a piece of apparatus called an electrophorus (fig. 8). A flat cake of resin is laid on the table. I rub it briskly with cat's fur and it is negatively electrified. I now put on it a flat piece of brass with an insulating handle of glass. The brass touches the resin in a few points and takes off the electrical condition from those points but not from the rest of the surface because resin is an insulator. I now touch the brass with a finger. The electrified resin attracts the positive electrical condition to the lower part of the brass. The negative is repelled through my finger and body to the earth. I remove my finger and lift up the brass by the glass handle. It is now positively electrified and you see I can get a spark from it and a slight shock by bringing my knuckle near it.

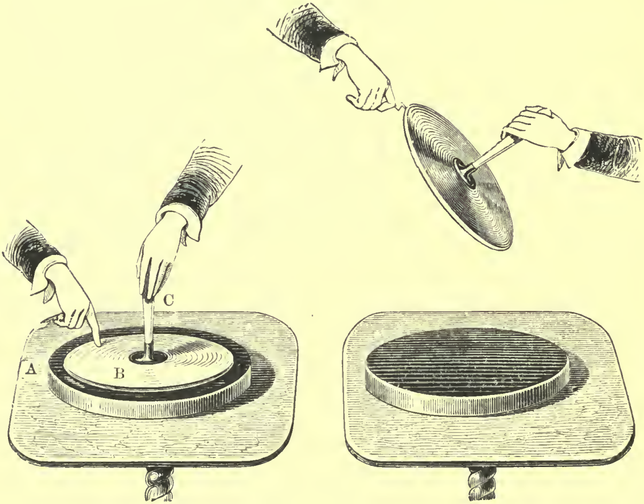

FIG. 8.—The Electrophorus.

A. Plate of resin, rubbed with cat's fur. B. Brass plate. C. Insulating handle. On touching B for a moment, and then removing it by the handle C, a spark can be got from B by approaching the finger to it.

Instead of taking the charge myself I may give the spark to the knob of this Leyden jar, a simple piece of apparatus which can hold a much larger quantity of the electrical condition than the brass sheet of the electrophorus. The potential of the electrification falls however in this process just as the pressure of steam falls when we pass it from a small vessel into a larger one. I can repeat this operation many times giving to the Leyden jar more and more of the electrical condition until it attains the same potential as the brass of the electrophorus and a spark no longer passes. The Leyden jar is now sufficiently charged to show the effects of this accumulation which has been going on. I connect one end of a wire with the outside of the jar, and on approaching another part of the wire to the knob of the jar you see a strong flash (fig. 9*a*).

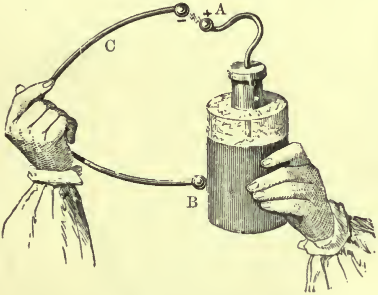

FIG. 9*a*.—Discharging a Leyden jar.

A. Knob of jar. B. Outside coating of tin-foil on jar C. Bent wire. A flash is produced when contact is nearly made.

Here I have still another application of induction. A glass vessel is filled with turpentine which is an insulator. I have two metal balls in it at a distance of four inches. These balls are connected metallically with the knobs of the Wimshurst machine. I have cut up some silk thread into short fibres which I sprinkle in the liquid. Turning the handle of the machine, I electrify the balls and the bits of fibre are electrified by induction, one end positively, the other negatively. They cling to each other end to end and form a strong connection between the two balls. I try to break this connection by means of a glass rod, but it shows great tenacity and elasticity, and returns to its position. This string of fibres is, of course, pulling at the positive and negative balls, and increasing the attractive force between them. Faraday thought that this illustrated well the kind of tension in an insulating medium such as air, which causes the attraction between oppositely electrified bodies.

A similar action is shown in an experiment of Professor Lodge's. You see that this large glass globe is now filled with smoke (fig. 9*b*). I introduce into it one end of a wire going to the Wimshurst machine. I turn the handle and the wire is electrified. The smoke consists of solid particles, which become polarized by induction and attract each other as the bits of silk fibre did. They become agglomerated, and fall to the bottom of the globe, and leave the globe, as you see it now, full only of the purest air.

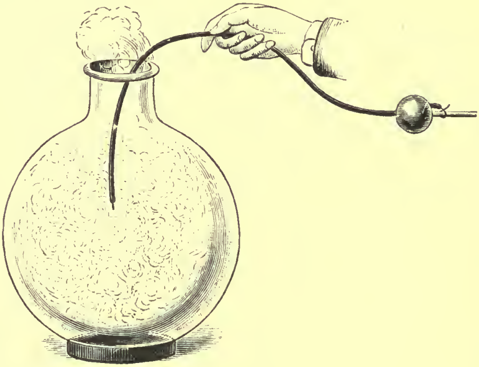

FIG. 9*b*.—Smoke electrified.

In all these experiments, during the extremely minute time that induction is taking place, and the electrical condition on the conductor is being rearranged, there is a motion of the positive condition in one direction and of the negative condition in the opposite direction. This action is spoken of as an electric current, and the direction of the current is said to be that in which the positive condition moves. During the passage of such electric currents through neighbouring conductors new and remarkable forces are exerted on the two conductors, causing apparent attractions and repulsions. But the present experiments are ill adapted for showing such phenomena, because the quantity of electrification is so small that the action lasts a very short time, perhaps a billionth of a second or less. These phenomena will form the subject of a future lecture.

I will now show you some advantages of using induction. Induction has led up to the construction of machines of very great simplicity, and I expect of great practical utility in the future. The first machine of the kind was Nicholson's doubler, which was simply an automatic means of accumulating an induced charge in a manner similar to the process I used with the electrophorus. Finally this has led up to the construction of such magnificent machines as this one (fig. 10) invented and made by Mr. Wimshurst.

I will now show some of the effects which can be obtained from such a powerful machine. You now see, when the handle is turned, the ordinary discharge of a bluish colour without noise and apparently continuous. This quantity of light in the discharge is a sign of a large quantity of electrification being generated; yet the quantity which is passing every second across this air-space is only about $\frac{1}{10000}$ of what is required for each of these glow-lamps overhead, which light the room electrically. But the electric potential is perhaps 500 times what is required for one of these glow-lamps. This machine would pass its current through 500 lamps in succession. But it would require 10,000 of these machines to give to the lamps the current which makes them so brilliant. The total energy in this discharge is about a twentieth of what is used in each of these glow-lamps.

I now connect the outside coatings of two Leyden jars together, and lead a wire from the knob of one jar to one knob of the machine, and use another wire to connect the knob of the other Leyden jar with the second knob of the machine. You now see a totally different effect. The electrification is now accumulated in the jars until the potential is sufficient to break down the air resistance of the space between the knobs of the machine, and then the accumulated power is let loose in a sudden and violent flash with a report like a small pistol. Thus I can get violent discharges across an air space of 8 inches. I reduce the

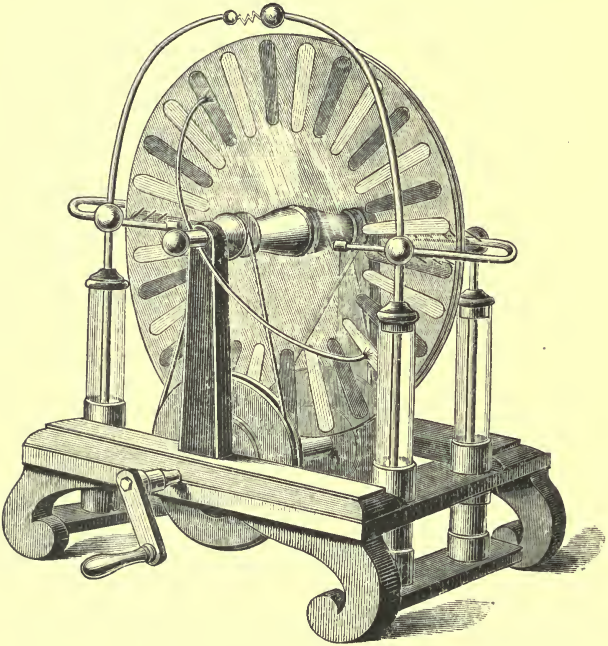

FIG. 10.—Wimshurst's machine.

distance to 4 inches, and the succession of sparks is now more rapid. When the distance is 2 inches, they seem to be continuous. We have now got a discharge giving off a light equal to about two candles, by which I can read comfortably except for the deafening noise. The expenditure of energy to produce the light is probably less than with any known system of electrical illumination. But as shown here it of course cannot be applied in practice.

You will notice that a spark can pass across 8 inches of air, but yet cannot pierce the glass of the Leyden jars, which is not a quarter-of-an-inch thick. This is a distinctive feature of different materials. Different materials offer different resistances to the mechanical strains introduced by electrification. This property is sometimes called *dielectric resistance.*

The distribution of electrification in equilibrium at the surface of a conductor is a subject of great interest, but I can only show you a few facts to-day. Here I have a metal ball suspended by a silk thread. I electrify it with the machine, I enclose it in two hemispherical metal cups which touch it, and which I hold by insulating handles. I now remove them and bring them to the gold-leaf electroscope. They are electrified, for the gold leaves separate. I bring the ball to the electroscope. The leaves do not move. The ball has lost its electrical condition. Why is this? The cups when in contact with the ball formed one conductor with it. The mutual repulsion of the electrical condition drives all that condition to the outside surface and thus now remains on the inner ball.

Faraday used the ingenious apparatus, a kind of butterfly net, which I hold in my hand by an insulating handle, to show that the electrification is all external (fig. 11). I electrify the net with the machine, and touch the inside with a piece of gilt paper on an insulating glass handle.

On bringing the gilt paper to the electroscope there is no sign of electrification. I do the same with the outside of the net, and you see that it is electrified. By a twist of the hand I turn the net inside out. I test the inside which is the part which we found to be electrified, and it shows no signs of electrification. The outside which was previously without electrification is now electrified as shown when I test it with the electroscope.

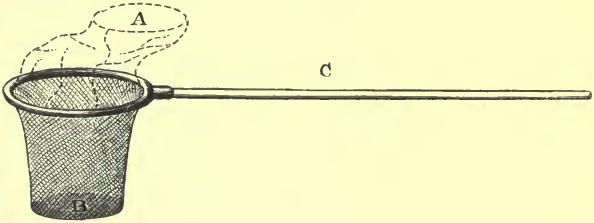

FIG. 11.—Faraday's Net.

B. Gauze netting. C. Glass handle. The inside cannot be electrified even when the net is turned inside out so that B takes position A.

Here I have a hollow metal ball or shell four inches in diameter with a projection inside projecting one inch towards the centre. I electrify the ball positively. You might expect the end of the projection to be electrified by a repulsion of positive electrification away from the nearest parts of the metal shell. The parts of the shell at the opposite side are farther away, three inches distant, but are larger in extent; is their repulsion able to neutralise the nearer action of the parts only one inch distant? Let us see. There is a hole at the side of the ball. I introduce a piece of gilt paper on a glass stem, and touch the projection. I bring the gilt paper to the electroscope and no action is shown. There is no electrification inside the conductor.

By referring to the diagram (fig. 12) you will see what this means. Part of the positively electrified shell is cut away to let us see the internal projection A B. Round the end A, I draw a circle C D, and from it draw lines through the end B, making a cone which cuts out another circle E F, at the opposite side of the shell. The whole surface can be thus cut up into opposing surfaces by cones passing through B. The surface E F is three times farther away from B than C D, and is nine times as large, and if the action of E F neutralises that of C D the action of a surface of definite area at three times the distance A B is only $\frac{1}{9}$th of the action of an equal area at the distance A B. But nine is the square of three. We express this by saying that the action of C D be neutralised by that of E F, if the forces are inversely as the squares of the distances. If this law holds, it is clear that each pair of opposing surfaces neutralises each other. If the repulsion of the smaller and nearer surface C D is the greatest, the point B will be positively electrified. If the repulsion of the larger and farther surface E F is the greatest, the point B will be left negatively electrified. Hence the non-electrified condition of the projection A B, which we got by experiment, is explained by supposing the repulsion of electrifications to be inversely as the squares of the distances. No other law would explain the experimental fact, when we have an internal projection, though any law involving repulsion would explain the symmetrical experiment with the cups enclosing a ball.

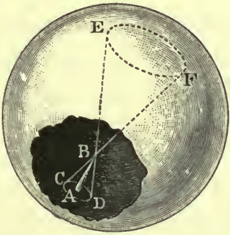

FIG. 12.—Diagram to show that the mutual repulsion of electrification varies inversely as the square of the distance.

With a pear-shaped conductor the electrification is greatest at the point of the pear, as you see when I bring a wire connected with the electrometer to different parts of the conductor. The electrification, if uniform, would be repelled by the large surface at one end much more than by the point at the other, and hence the potential at the point would accumulate until there was equilibrium.

The potential at the point of a wire or the edge of a thin sheet of metal may be so great that the dielectric resistance of the air is overcome and the wire or sheet of metal is discharged.

Having now shown you the phenomena of attraction, repulsion and induction, I would ask you whether you feel satisfied with the old view which used to be held, according to which electricity is a fluid material which settles upon the surface of an electrified body, and, acting across the intervening space by a kind of action at a distance, causes attraction and repulsion of other bodies, and also causes attraction and repulsion of the fluid on a conductor. The question of the possibility of action at a distance is an old one which meets us when we study gravitation and other physical forces, and for myself it is inconceivable that the sun for example can be endowed with something like a mesmeric power by which it is able to will the distant planets to approach it. Still more inconceivable is it to me that this rubbed glass rod can divine whether another object in its neighbourhood is positively or negatively electrified, and so will that distant body to approach to or recede from it. To me the notion of such action at a distance is so inconceivably absurd, so beyond the province of the natural philosopher, that it passes altogether into a pseudo-metaphysical question. Does it not seem to you that all these actions must be due to the intervening action of something (call it the ether if you will) existing between the mutually acting bodies? The existence of such a medium seems to be necessary for an ultimate explanation of gravity and electricity. We are almost certain that such a medium does exist. The theory of light has almost conclusively proved that there is such a medium pervading all space and penetrating between the molecules of material bodies. It is possible that the same medium which gives rise to radiation of heat and light is also the cause of the phenomena we have been considering.

It was our great philosopher Faraday who realised that all electrical phenomena are produced by the electrification of a medium which fills all space. Is this the same medium as the luminiferous ether? How can we test this? We know from our study of light that the ether between the molecules of air has different properties from the ether between the molecules of glass or other materials. Faraday, led perhaps by such thoughts, asked himself 'Does the induction in a certain space vary when different insulating materials occupy that space?' He appealed to experiment, and he received the most important reply which experiment ever gave him, which was simply the word 'yes,' in the clearest and loudest tones in which experiment can speak.

I fix an electrified ball over the disc of an electroscope. Induction takes place through air, and a slight divergence of the gold leaves is apparent. I now take a cake of sulphur, and, after passing a flame over its surface to remove all traces of electrification, I interpose it between the electrified ball and the disc of the electroscope. The leaves diverge farther. The induction through sulphur is proved to be greater than through air, clearly showing that induction depends upon the intervening medium. This brilliant discovery of Faraday's was extended and confirmed by a laborious research.

Twice during this lecture I have used a Leyden jar for condensing or accumulating a charge of the electrical condition. It consists simply of two sheets of metal (tinfoil is convenient) separated by a piece of insulating material such as glass. Other condensers are often made flat, but the jar shape is convenient because there is less chance of the inner and outer coatings becoming neutralised by conduction over the surface of the glass, if it be slightly coated with condensed moisture. Its power was accidentally discovered by a philosopher of Leyden, hence its name. If I connect the outer and inner coatings of tinfoil with the two knobs of the Wimshurst machine, induction takes place in the glass separating the coating. If the potential is raised very high, the mechanical strain in the glass produced by induction may overcome the dielectric resistance of the glass and pierce it, though it be a quarter-of-an-inch thick. The hole pierced is then full of air whose resistance can be overcome by a much lower potential. So that when the glass of a Leyden jar is pierced we cannot charge it to a high potential. Here I have two specimens of glass, one of them an inch thick, which have been pierced by the powerful induction coil of the late Mr. Spottiswoode. In practical applications of electricity, in constructing dynamo machines for example, when we use high differences of potential, we must take care to insulate our conductors with material which has a high dielectric resistance.

All these facts involve the notion of a mechanical strain in the insulating material. This led Faraday to adopt the view that in all the electrical phenomena we have been studying the action is taking place only in the medium separating the electrified conductors; and that it is really the medium which is electrified. He showed that it was impossible to give an absolute positive or negative charge to one substance without at the same time giving an equal but opposite charge to another; and that there are always lines of inductive action through the space separating such electrified bodies. The direction of such lines of induction through an air space is shown by hanging an electrified pith ball by a silk fibre in different parts of that space. The direction of its motion shows the direction of the induction (or more exactly the horizontal component of it). His idea, now universally accepted, was that we must abolish the idea of electricity being a material, abolish the idea of bodies being charged with electricity; where there is equilibrium we never find proofs of electrification in the mass of the conductor, but only in the mass of the insulating medium, and at that part of the medium which forms the boundary of the conductor.

In illustration of these remarks I will now show you an experiment with a Leyden jar which can be taken to pieces. I remove the inner and outer coatings and touch the electroscope with them. They hardly show a sign of electrification. It is the strain in the glass which gave the Leyden jar its power. I replace the coatings which are not electrified. The strained glass can now act through them. On connecting the two coatings I get a spark.

The poles of my electrical machine are connected with the inside and outside of a Leyden jar. After charging I discharge it, but the glass has not got rid of its strain and on again connecting the knobs you see I get another spark.

It is sometimes possible to get a considerable number of discharges in the same way. I can show you a remarkable example with the help of a piece of material called dermatite lent me by Mr. Wimshurst. I stand upon it and hold the knob of the electrical machine while the handle is being turned. Inductive action is now going on in the sheet of dermatite between my body and the floor. I am now positively charged, and we will see if Mr. Davenport can take sparks from my fingers. [Nine successive sparks, the last very feeble, were produced.]

Had it not been that this material takes a long time to get rid of its strain, the first discharge would have completely discharged the electrical state. But, probably owing to its being made of layers differing in their insulating powers, it takes some time to discharge and so you saw a succession of sparks.

I will show you now another very striking experiment to prove that the induction in glass is a state of strain. After discharging a Leyden jar, I connect its inner coating with the electrometer, the outer coating being on the table. The jar has still some strain to get rid of, as is shown by the increasing motion of the spot of light which marks the movements of the index of the electrometer. The rate at which the spot of light is moving shows the rate at which the strain is being got rid of. Now I give the jar a few sharp taps, and the spot moves two or three times as quickly. What do these taps do to the glass? They help the glass to get rid of its state of mechanical strain. An increased rate of getting rid of mechanical strain is accompanied by an increased difference of potential between the coatings of the Leyden jar.

No doubt the strain in the glass acts by affecting the ether which is associated with the molecules of glass, and it is easy for me to show you that mechanical strain of glass does affect the luminiferous ether. Here is an electric lamp, by means of which I can throw a beam of light upon the screen. In the course of the beam I interpose two transparent Nicol's prisms, as they are called, kindly lent me by Dr. De la Rue. They have a remarkable property of only allowing part of the vibrations which constitute light to pass through them. As arranged at present the first one only allows up and down vibrations to pass through, and the second one only allows horizontal vibrations to pass through, and so no light can pass through both of them, so that we get no light upon

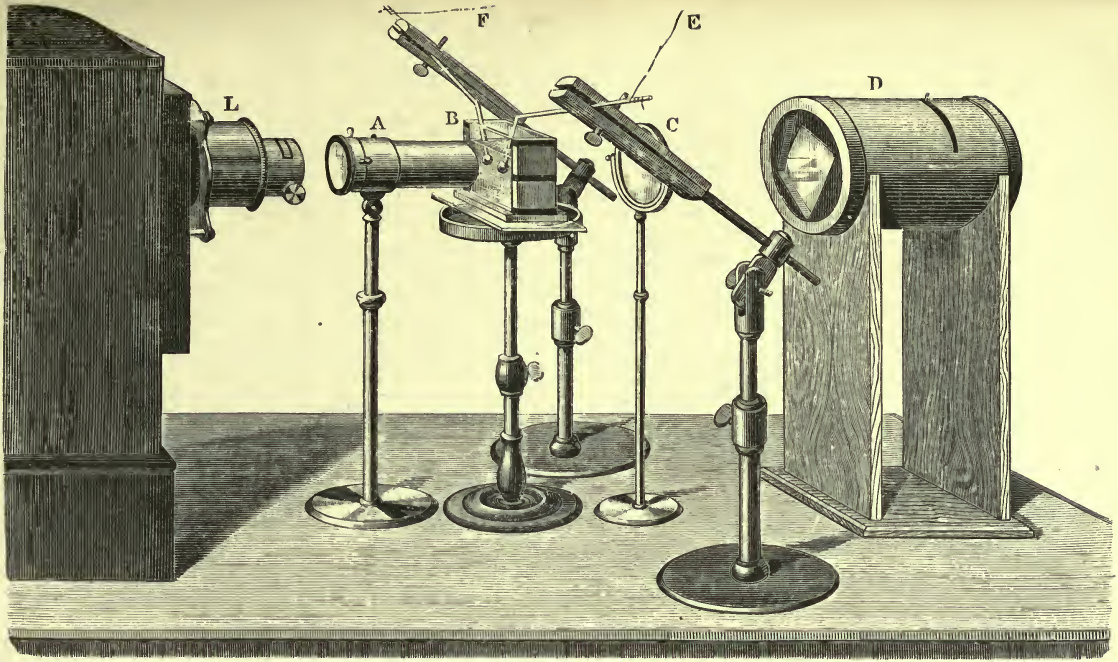

FIG. 13.

L. Electric lamp. A and D. Nicol's prisms. B. A glass cell containing bisulphide of carbon (taking the place of the glass). F, E. Wires to Wimshurst machine. C. A lens.

the screen. By turning the second one about the beam of light as an axis through ninety degrees, it allows up and down vibrations to pass, and you see the screen illuminated. I replace them in the dark position. There is no light on the screen. I now put a piece of glass between the two prisms where it is struck by the up and down vibrations. Still there is no light on the screen. Now I give a mechanical twist to the glass. It changes the direction of the vibrations and you see light on the screen. Now light is propagated through the ether, but the mechanical strain on the glass acts as a strain upon the ether. So also in the electrical phenomenon it is quite likely that it is the ether which produces the phenomena of induction when the glass is strained. Faraday contented himself with showing that all the phenomena of electrical equilibrium can be accounted for by supposing the insulating medium to be strained. Clerk Maxwell gave reasons for believing that the same ether performs the functions for radiant light or heat and for electricity. Maxwell extended Faraday's views considerably and proved mathematically that if we can suppose the medium to be in a state of tension along the lines of induction (just as the bundle of silk fibres in turpentine were in a state of tension along the line of induction in a previous experiment), and if we can further suppose that there is an equal pressure tending to extend the medium in directions at right angles to the induction, then all the phenomena of electricity in equilibrium can be explained.

It becomes highly important then to show that the strain in electrified glass is in the direction indicated by Faraday and Clerk Maxwell. To do this I make use of the electric lamp, Nicol's prisms and screen (fig. 13) which we have just been using, but instead of the mechanically strained glass I insert a piece of electrically strained glass. The glass slab has holes in it through two opposite edges, nearly meeting in the middle.[1] I have wires in these holes whose ends, one-quarter-of-an-inch apart, are separated by the glass. These wires go to the knobs of the Wimshurst machine. We have darkness on the screen now, but when I turn the handle of the machine light appears, showing the strain produced electrically. This experiment was first made successfully by Dr. Kerr of Glasgow, and by means of such apparatus he was able to prove that the direction of the strain was the same as theory predicted.

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[1] In the figure the slab of glass is replaced by a dish containing bisulphide of carbon. Two glass tubes with bulbs full of mercury form the points of connection to the machine.

LECTURE II.

ELECTRIC CURRENT AND RESISTANCE.

In the last lecture I showed you that any space not occupied by a conductor can become electrified or strained in such a way as to produce attractions and repulsions on the bodies which bound that electrically strained space. In any such space there is an electromotive force which is capable of creating a momentary current in any material which is a conductor, giving rise to a rearrangement of the electrification by the process known as induction. This principle of induction enables us to understand the significance of innumerable experiments. I could multiply examples and would gladly do so but that I prefer to concentrate our attention on the special parts of electrical science, which are now being so much applied to practical purposes. During the act of induction in a conductor, an electric current, momentary in duration, passes along the conductor. So also when I touch one end of a wire with an electrified body, an electric current passes along the wire. But the capacity, as we call it, of any electrified body is so small, that these currents are insignificant compared with the effects we can get by using galvanic batteries as the source of our electricity. This is the kind of current we shall be examining in the future. But I wish you to realise that the electric currents we are proceeding to study are exactly the same in character as those obtained when we touch two ends of a wire with oppositely electrified bodies. The electric current which passes to the earth during a lightning flash, infinitesimal though its duration may be, is identically of the same character as the electric current which passes from batteries through the telegraph instruments, or which is lighting up this room by means of these glow-lamps.

It is hardly necessary now to insist upon this, but there was a time, not so long ago, when it required the laborious researches of our most able experimenters to prove that all electric currents however generated are the same in character and produce the same kind of effects, thermal, chemical, magnetic, and physiological.

I will, however, show you these experiments with the Wimshurst machine to illustrate the fact that heating effects, magnetic effects, and chemical effects can be obtained from its currents. You will afterwards have abundant evidence that the same effects are produced by the current of a galvanic battery. I have here a small strip of tinfoil between two plates of glass. I subject it to an electromotive force by putting it between the two knobs of the Wimshurst machine, and then working the machine. Now the spark passes. A current has flowed through the foil and heated it to the fusing point, and its particles are scattered right and left on the glass, leaving a mark which reminds me of the scattering of sand when a string of dynamite cartridges has been exploded upon the sea-beach (fig. 1). Here is another specimen in which the effect is even more powerfully shown, because not only has the tin-

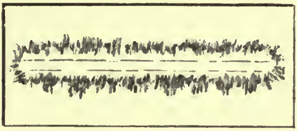


FIG. 1.—Marks left on a piece of glass by tinfoil fused by the current from an electrical machine.

foil been actually fused, but the glass has been shattered by the power of the discharge.

The quantity of electricity which flows in the minute time occupied by this discharge is very small. In fact Faraday stated that in the most powerful lightning flash there is not so much electricity passing as there is at the time when we decompose a single drop of water by the electric current.

I will now show you a magnetic effect of the discharge, using for this a battery of Leyden jars to accumulate the electricity, and so increase the instantaneous current occurring during discharge. I have two knitting-needles which, as you see, do not produce any marked movement in a compass-needle when brought near it. They are not magnetised. I place one of them, as you see, below and the other above a strip of sheet copper (fig. 2). Both needles are pointing towards you, and I shall connect the ends of the copper strip with the inside and outside of the Leyden jars so that the positive electrical condition has to flow from your right to your left, and the negative in the opposite direction. There, now the powerful discharge has passed. I suspend each knitting-needle by a thread. They both point north and south, but I have painted the ends which were towards you white. You see that the white end of

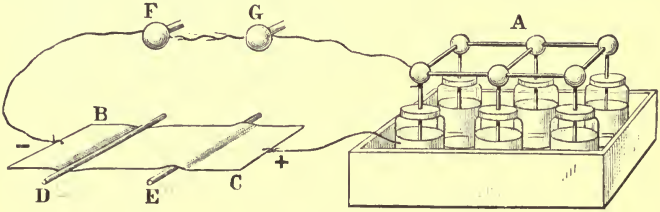


FIG. 2.

A. Battery of Leyden jars. B C. A strip of copper. D and E. Two unmagnetised knitting-needles. G. A knob connected with the negative insides of the Leyden jars. F. A knob connected through the copper strip with the positive outside of the jars. After the spark passes between F and G, the end E of one wire tends to point to the north, and D to the south.

the one which was under the copper strip points to the north, the white end of the other points to the south. You can hardly yet appreciate the significance of this experiment until you have seen that exactly similar effects occur with a galvanic cell as the source of electromotive force.

I will now show you that the discharge from the machine can decompose a solution of sulphate of copper and deposit copper on the negatively electrified conductor which is in the solution. Here I have a glass plate with two pieces of tinfoil fastened to it (fig. 3). They are connected, one with a piece of wire, the other with a wet string, to the two knobs of the Wimshurst machine. With a paint-brush dipped in a solution of sulphate of copper I draw a rough line on the glass, and, after twisting into convenient form two pieces of platinum wire, I place each in contact with one of the pieces of tinfoil, and the point of each wire at one end of the line of sulphate of copper solution. I now pass the discharge from the machine. The wet string being a poor conductor makes the discharge more gradual and without sparks. After a minute I now

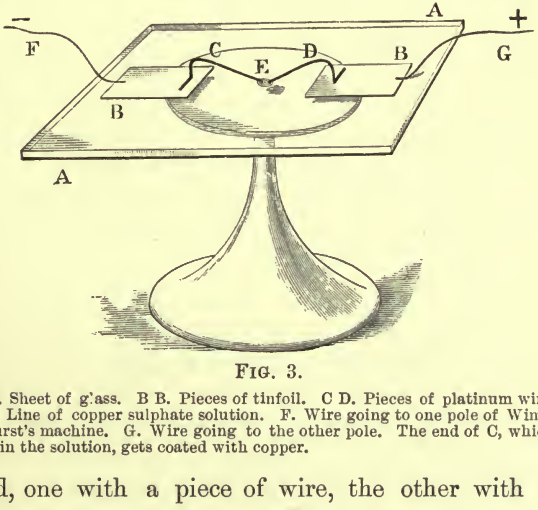


FIG. 3.

A A. Sheet of glass. B B. Pieces of tinfoil. C D. Pieces of platinum wire. E. Line of copper sulphate solution. F. Wire going to one pole of Wimshurst's machine. G. Wire going to the other pole. The end of C, which is in the solution, gets coated with copper.

stop the action and remove the platinum which was negatively electrified. I will pass it round to you, and you can see it is covered with copper. The positive one is not affected.

It appears that the effects of an electric current can be produced either by the passage of an electrical condition through a conductor, or else by the bodily transference of an electrical conductor which is electrified. If I hold a conductor by an insulating handle and make it touch the two electrified knobs of the machine alternately, I am always carrying positive electrification in one direction or negative in the opposite direction. We have reasons for supposing that this action is the same as an electric current. Some years ago Professor Rowland showed that by charging a body with electricity, and moving it with great rapidity he was able to produce effects like those due to an electric current, and to cause the deflection of a compass-needle. I believe that his experiment has never been successfully repeated.

I will now show you some simple means by which an electric current can be produced, and I will begin by showing upon the screen an image of a glass cell containing water with a little sulphuric acid in it. Now I introduce a copper wire into it; you see its image sharply in focus; there is no bubbling of gas near it. I now introduce a piece of pure zinc in place of the copper and there is no gas. I will next introduce them simultaneously—the zinc and the copper—and still there is no sign of gas. But now notice, so soon as I touch the wires there is an evolution of gas rising from the copper in bubbles; on the screen the bubbles go downwards because the image of the cell is inverted (fig. 4). This is the gas hydrogen, and it shows that the mere contact of the metals when dipping in the water makes a great difference. The hydrogen can only come from the acidulated water which contains hydrogen. It appears, then, that chemical decomposition of the liquid is going on when the metals touch.

On a chemical examination of the products of this action it is found that the quantity of water in the cell is not altered, that the quantity of sulphuric acid diminishes, that zinc sulphate is formed in its place, and that hydrogen gas is given off at the copper plate. Now zinc sulphate differs in its constitution from sulphuric acid only by the substitution of zinc for hydrogen in its molecules. But this substitution of zinc sulphate for sulphuric acid occurs only on the surface of the zinc, the hydrogen is formed only on the surface of the copper. There must then be an interchange of hydrogen between the molecules that lie between these two positions. While this action is going on we find that a transference of electrification is taking place in a complete circuit, through the liquid and two metals back to the liquid. This is an electric current whose effects we shall observe immediately. But whether the chemical action is the result of the electricity, or the latter the result of the former, I cannot tell you. This is certain, that pure zinc is not acted on by the liquid unless another conductor, as copper, completes the circuit.

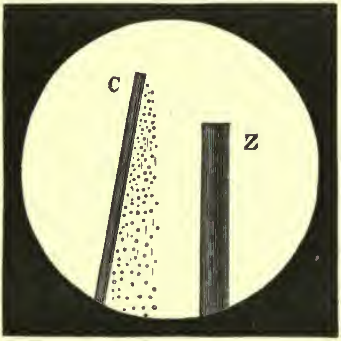


FIG. 4.

This chemical action under the influence of electricity, has been explained or rather illustrated by the accompanying diagram, fig. 5 (*a*) and (*b*).

A molecule of water is made up of an atom of oxygen, combined with two atoms of hydrogen. The diagram shows the arrangement of a string of molecules between the zinc and copper.; each small square is oxygen, each large one hydrogen. The positive zinc attracts oxygen which is negative, and this accounts for the polarized arrangement of the atoms in the water molecules. When a wire connects the zinc and copper, the action in fig. 5 (*b*) takes place. A zinc atom combines with an oxygen atom. A recombination of oxygen and hydrogen takes place all along the line, leaving hydrogen free at the copper. These new molecules now turn round till they take the positions in fig. 5 (*a*), and the process is repeated. After the above action, the zinc, which has formed zinc oxide, changes place with the hydrogen of the sulphuric acid, thus forming molecules of zinc sulphate and water.

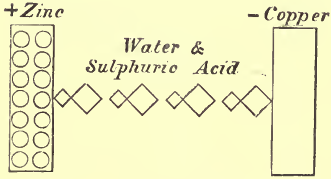


FIG. 5 (*a*).

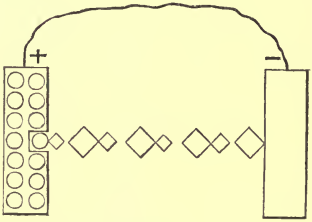


FIG. 5 (*b*).

We found in our last lecture that when zinc and copper are in contact the zinc is positively, the copper negatively electrified. It is possible that this is just the impetus that is required to separate the molecule of water, sending the oxygen part (negative) to the positive zinc, and hydrogen to the negative copper. It is quite conceivable that in some such way the electric and chemical actions are related. There are some who go so far as to think that the chemical affinity of atoms for each other is merely an electrical attraction, and that all chemical action is equivalent to the production of local electric currents. But all this is in the realm of hypothesis, and no theory has been established which completely and conclusively explains electro-chemical action.

The simple cell which you have now seen is called a galvanic cell (fig. 6). Here I have a larger cell of the same sort. I have a copper plate and a zinc plate with copper wires attached, going to the external conducting circuit. According to what we have noticed before, the copper wire connected to the zinc is negative, whilst the positive of the zinc passes through the liquid and the copper plate, to the attached wire. If the two wires be now connected by a conducting circuit, a current of positive electricity passes from the wire attached to the copper through the circuit to the wire attached to the zinc.

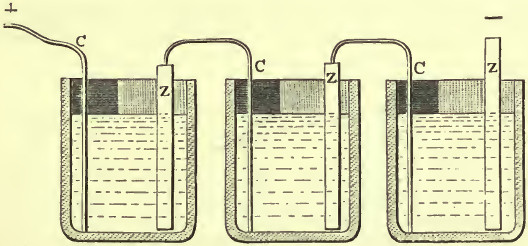


FIG. 6.—Simple Galvanic Cell.

I will now show you some more chemical actions which take place under the action of these positive (+) and negative (—) terminals. I connect these terminals to two strips of platinum which I place under the water contained in a test-tube. The water has a little acid in it to increase its electrical conducting power. Platinum is used because it cannot be acted upon by oxygen.

You now see bubbles of gas given off in the liquid of the test-tube (fig. 7). These gases are oxygen and hydrogen, the components of water. The test-tube is now full. I lift it up and bring the mouth of it to a flame, and a loud explosion occurs, giving you some notion of the energy which is being converted into heat when oxygen and hydrogen combine to form water. I can have the two platinum terminals each in a separate test-tube, and now you will find that negative oxygen is given off at the terminal connected with the copper of my galvanic battery, and hydrogen at the other. The tubes are nearly filled, and when they are full I will test them to show you that this is the case. Here is the test-tube which was connected with the zinc of the cell; I approach a lighted taper to it and it burns with the blue flame of hydrogen, and you now see the flame descending the tube as the hydrogen is consumed. I now blow out the taper but leave it smouldering. I introduce it into the test-tube which was connected with the copper, and the taper bursts into flame. This test shows that we have oxygen in the tube.

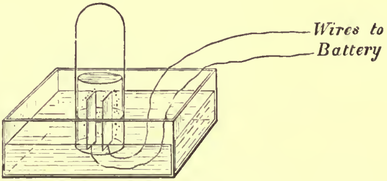


FIG. 7.—Decomposition of water by the electric current.

I now throw upon the screen an image of a glass cell containing a solution of sulphate of copper. I introduce into it the two copper wires which are the terminals of my galvanic cell. You now see an accretion of particles on the wire coming from the zinc (the negative wire). These particles are pure copper. The sulphate of copper is decomposed; positive copper being deposited on the negative terminal, and copper being dissolved from the positive one. Thus the strength of the solution remains unaltered. If in place of a copper wire I place any other conducting material in the liquid as a negative terminal, it becomes coated with copper.

This simple experiment contains the essence of the whole art of electro-plating.

I will show you one more experiment to illustrate the chemical action of the electric current. Here I have a steel plate highly polished. I put it into this vessel which I shall fill with a solution of acetate of lead. Over it I place the point of a wire which is attached to the zinc plate of a galvanic cell. I now fill the vessel with the solution, and connect the steel plate with the copper of the cell. Chemical action is now going on, and an oxide of lead is being deposited on the steel in a thin film whose thickness is greatest near to the point of the wire. Thus we have different thicknesses on concentric circles, and these show the beautiful iridescent colours of thin plates which Sir Isaac Newton studied in another way (fig. 9). This experiment was devised by an Italian philosopher called Nobili.

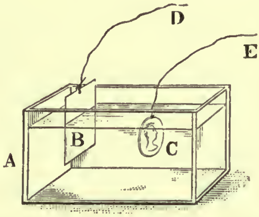


FIG. 8.—Process of copper-plating.

A. Cell containing solution of sulphate of copper. B. Copper plate. C. Medal. D E. Wires going to copper and zinc respectively of the galvanic cell. The medal becomes coated with pure copper.

These methods of electro-chemistry have been much applied in practice. By this means gold, silver, copper, and nickel are extracted from liquid solutions and deposited upon articles connected with the zinc of a battery. Thousands of tons of pure copper are also obtained from impure metal by this means. I venture to predict that before long all copper kitchen utensils will be thus made, and in the same way, perhaps, ships' bottoms will be coppered.

Hitherto I have used a typical form of battery consisting of copper and zinc plates immersed in water diluted with acid. In such a battery you have seen that hydrogen collects on the copper plate. Now hydrogen is positive and copper negative. Thus a counter electromotive force is established. But if we have in our conducting circuit two electromotive forces in opposite directions they tend to neutralise each other. This is made manifest by a weakening of the current which we get from our battery. To prevent this action we must prevent the hydrogen from touching the copper. This is accomplished in Daniell's cell which I now show you by putting the copper into a porous pot containing sulphate of copper, which absorbs the hydrogen. Other batteries have round the negative metal either oxide of copper, or lead peroxide, or oxide of man-

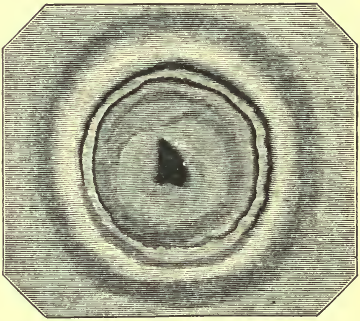


FIG. 9.—Nobili's rings produced by a deposit from acetate of lead, and showing the beautiful colours of thin plates.

ganese, or nitric acid, or any other oxidising material which combines with the hydrogen. A cell thus prepared is called a *constant cell.* If I take two cells and join the two zincs by wires and the two coppers, if you consider the conducting circuit you will see that the electromotive forces of the two cells act in opposite directions. Hence we get no effect. If I connect the zinc of one to the copper of the other by wires, the electromotive force of each cell assists that of the other and the whole conducting circuit is acted upon by double the electromotive force. When we want to obtain very powerful effects, we connect a great many cells in this way in series and thus obtain a powerful battery. Dr. W. de la Rue thus connected 14,000 cells, and obtained an electromotive force comparable with what we get from a Wimshurst machine.

I cannot increase the electromotive force of a cell by enlarging its dimensions. This force depends only on the chemical constituents of the cell, not on its dimensions. I can show this to you in a very convincing manner. Here (fig. 10) I have a small copper and zinc cell made out of a copper percussion cap of a rifle, inside which is a piece of zinc wire wrapped in blotting paper which is moistened. Again I have a large cell with plates of copper and zinc a foot square. I have also a galvanometer or instrument for detecting electric currents. It consists of a compass-needle with an index, freely suspended inside a coil of wire. Each turn of the wire is electrically insulated from its neighbour by a coating of silk so that the electric current is compelled to pass through all the coils. One end of the wire is attached to the zinc of the large cell, the other to the zinc of the small cell. The two coppers are connected by wire. The electromotive forces of the large and small cells are acting in opposite directions on the same circuit, and now we shall see by the index of the galvanometer which is the strongest. If you watch the galvanometer while I introduce the zinc into the small cell and so complete the circuit, you can see the deflection. It is now introduced, and there is no perceptible deflection. This proves to us that the opposing electromotive forces of the large and small cells are equal to each other.

I now connect the wire from the percussion cap, direct to the galvanometer, thus cutting out the large cell from the conducting circuit, and you see a powerful deflection.

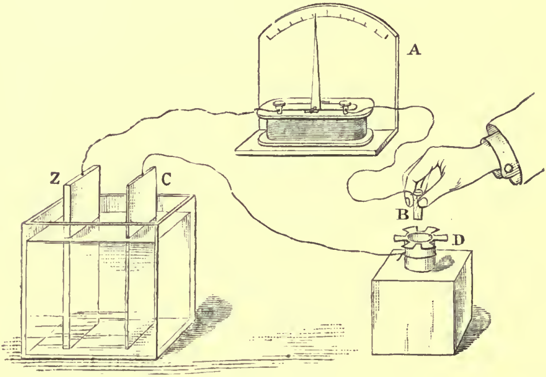


FIG. 10.

A. Galvanometer. Z. Large zinc plate connected to galvanometer. B. Small zinc wrapped in moist blotting paper. C. Large copper plate connected by wire to percussion cap D. On placing B in D no movement of the galvanometer's index is seen.

I must now show you still another means which we have of obtaining a constant current of electricity. This department of our science is called thermo-electricity. I will make use of the same galvanometer as in the last experiment. I attach an iron and a copper wire to the two ends of the coil of the galvanometer. The other ends of the copper and iron wires are twisted together to form a metallic junction. I hold this junction in the flame of a spirit lamp and the galvanometer index is deflected to the right showing an electromotive force from the copper to the iron through the hot junction. I now put the junction upon ice. There is a deflection in the opposite direction, which indicates an opposite electromotive force, going from iron to copper, through the cold junction. The metals bismuth and antimony act still more powerfully, and instruments can be made out of these metals which can detect the feeblest traces of heat. Here I have a tube made of two half-cylinders of antimony and bismuth, respectively soldered to make one short tube. A magnetised needle hangs inside the tube by a silk fibre, and a light mirror is attached to the magnet which reflects a beam of light on to a scale. If one junction is hotter than the other, a current flows and deflects the needle, and so moves the spot of light. The radiation from a candle at a distance of several yards is sufficient to show a marked deflection.

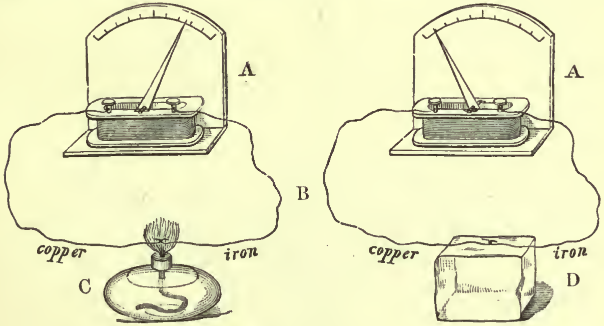


FIG. 11.

A. Galvanometer. B. Junction of iron and copper wires. C. Spirit lamp. D. Block of ice. Heat and cold deflect the index in opposite directions.

I have here (fig. 12) a still more sensitive arrangement made for me by Messrs Nalder.

Thermo-electric batteries of considerable power have been made; here is the well-known battery of M. Clamond. It consists of a number of elements connected into a continuous series. Each element consists of a strip of iron and a bar of alloy. The alloy is a mixture of zinc and antimony. There are seventy-five strips of iron and the same number of bars of alloy. These bars and strips are soldered together in alternate order in such a way that every alternate junction comes to the inside of the cylindrical pile and the other alternate junction to the outside. The heat from a Bunsen gas-burner passes up through the axis of the cylinder, heating the alternate junctions. The outer junctions are cooled by radiation and by contact with the air of the room. The two ends of this series of metallic elements have brass binding screws attached which can be connected by a wire or other conductor through which we wish to pass an electric current. I will cause this current

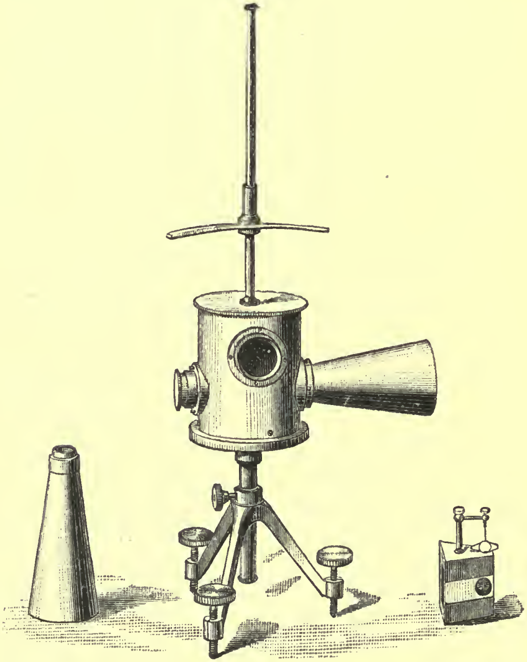


FIG. 12.—Professor Forbes's Thermopile Galvanometer.

to pass through the apparatus we have already used for decomposing water. Now, as when we used a battery, we have a complete conducting circuit, and in this circuit we have seventy-five electromotive forces, all urging the positive electrical condition in the same direction through the hot junctions to the iron, and through the cold junctions to the alloy. You see that this intensified force is able to overcome the resistance opposed by the water, and to decompose it into its constituent elements, oxygen gas and hydrogen gas, which rise in bubbles through the liquid.

In all these cases the electrical energy of the current is derived directly from energy in the form of heat. Heat is absorbed at one junction, is conducted along the metals, and is given off at the colder parts of the metals. The total heat thus given off is less than the total heat absorbed. The difference represents an amount of energy which is the exact equivalent of the electrical energy of the current. The electromotive force may be created either at the junction where heat is absorbed, in which case the heat absorbed is greater than the heat conducted. Or again the electromotive force may be created during the process of heat-conduction in which case the heat which is conducted towards the cold junction is not all given off to the air

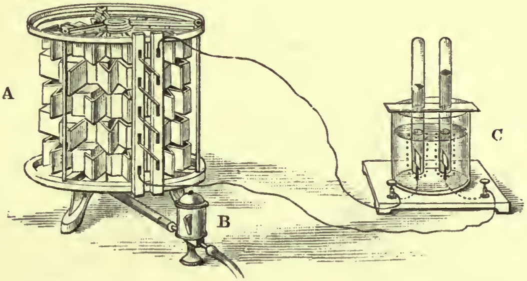


FIG. 13.

A. Clamond's thermo-electric battery of 75 elements. B. Bunsen gas-burner. C. Voltameter in which water is decomposed.

when the conducting circuit is closed and a current passes. It has been found by experiment that both of these effects take place. Thus we find that when an electric current flows through a bismuth and antimony junction, from the former to the latter, heat is absorbed there.

To show you this, I make use of a strip of metal, partly bismuth and partly antimony, with a little trough at their junction. I put a drop of ice-cold water into the trough and lay the metal on a piece of flannel which does not conduct heat readily. I pass a current from a battery from the bismuth to the antimony, and in a few minutes the water will be frozen.

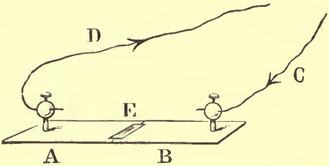


FIG. 14.—Freezing of water.

A. Antimony. B. Bismuth. E. Drop of water. C. Wire going to copper of battery. D. Wire going to zinc of battery.

Many years ago Sir William Thomson showed, having predicted such an effect by theory, that if a bar of iron be heated at its centre, and an electric current passed along the bar the point of maximum heating is moved in the opposite direction to that in which the current flows.

Now returning to the experiment I see that the water is frozen. There is now a small piece of ice at the junction of the metals. I pick it out with a knife and let it drop on this tin vessel. You hear the noise of its fall which tells you that the water has been solidified.

In all the experiments in which we have maintained an electric current, you have noticed that there is a closed conducting circuit, and in the course of this circuit there are one or more sources of electromotive force, and a current passes round the circuit only when the sum of electromotive forces tending to cause a current in one direction round the circuit is greater than the sum of those acting the opposite way.

The force of gravity is something which causes motion or tends to cause motion in a mass. It causes motion when a stone is falling through air which offers but little resistance. It *tends* to cause motion (but only produces pressure) when a weight rests on a table. The table offers a resistance to the motion of the mass. If the table were made of putty this resistance would be much less and some motion would take place. So also our electromotive force causes motion or tends to cause motion of the electrical condition. It causes motion when an electric current is flowing through a metallic circuit which offers but little resistance. It tends to cause motion (but only produces strain) when the circuit is interrupted by an insulator like air. The air offers a resistance to the motion of the electrified condition. If the air were replaced by water or a solution of sulphate of copper, the resistance would be much less and some motion of the electrical condition would take place.

It would appear then that the intensity of the current circulating in any conducting circuit depends upon the sum of the electromotive forces in the circuit and on the sum of the resistances in the circuit. The greater the electromotive force the greater the current, the greater the resistance the less the current.

But the resistance of a conductor depends on its dimensions as well as on its material. The greater its length the greater is the resistance. The greater its sectional area the less is the resistance. I have here a battery with a definite electromotive force. I connect its terminals with the two ends of a thread of carbon in this glow-lamp. The carbon offers a certain resistance which determines the strength of current through it. You see the evidence of a considerable current in the intense incandescence of the carbon heated by it. I now make the carbon thread twice as long by connecting two lamps in series. The resistance of the battery and conducting wires is very small, so that I have now doubled the resistance of the circuit and you see the effect of having only half the current. The carbon threads are only a dull-red owing to the feebler current.

But if my conductors be of equal length and the same material, the thickest one has the least resistance and allows most current to flow if both are influenced by the same difference of electrical potential at the two ends. Here I have two platinum wires of equal length, but of different diameters, suspended horizontally, and connected at their two ends, where they are attached by wires to the battery. Now the thick wire glows brightly and the thin one is barely luminous. Clearly there is more current passing through the thick wire. Its resistance is less.

In many applications of electricity a battery is part of the circuit, and the resistance of the battery is part of the resistance of the circuit. Clearly this resistance is diminished by bringing the plates closer together and by increasing the surface of the plates. Here I have a zinc and copper cell connected to the galvanometer which we used before. I have the zinc plate fully immersed, and the copper plate just dipping in the acidulated water, and you see we have a deflection on the galvanometer of 45 degrees. Now I can vary the conditions of the experiment by varying the resistance of the battery. I lower the copper plate into the liquid, and so increase the sectional area of liquid through which the current passes, and as I do so the deflection of the index of the galvanometer immediately increases; and now the index is permanently deflected quite to the end of the scale, showing the decrease in resistance and the increase in current. In the same way, if I bring the plates nearer together, the resistance is less, and consequently we get a greater deflection.

You see that the resistance of the liquid of the battery depends on the distance the current has to go through it, and on the section of the liquid traversed by the current. I will pursue the experiment one step further to show you how the resistance is affected by the constitution of the liquid. Here I have a cell exactly like the one we have been using, except that it contains pure distilled water. The zinc and copper plates are quite clean. They are connected with the galvanometer. I immerse them fully into the liquid, but the movement of the galvanometer is very slight. The resistance of distilled water is very great indeed. Now I put in a single crystal of common salt weighing far less than a grain, and stir it to dissolve it. Now you see the index of the galvanometer has moved, showing that the resistance of the liquid is diminished. I add a little more salt, and the index moves to the end of the scale.

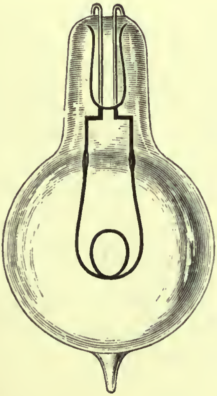
When a real force has acted upon a mass of matter to set it in motion, that mass would move on for ever in the same direction if no force acted upon it. When a ball is rolled along the ground or even on the ice of a frozen lake it does not go on for ever, because the force of friction stops it. The force of friction between the ball and the ground is a resistance, and the energy of motion is converted into energy of heat. In the case I speak of you cannot detect the heat, but when the energy of motion of a railway train is stopped by the resistance of the brake you see sparks flying and you can feel that the brake is warm.

When the electrical condition has been set into motion round a conducting circuit it would go on for ever if no force acted on it. But we find in experiment that after the electromotive force has ceased to act the current stops.

The wire offers resistance to the current just as water offers resistance to the motion of a ship, and stops it. The electric current certainly has energy, though it is not the energy of motion of matter. We know it has energy because we know it can do work. Now we are as sure of the truth of the principle of conservation of energy as we are of the law of gravity; and that principle tells us that energy cannot be destroyed, though it may be transformed. When the electric current ceases, its energy is not destroyed but is transformed into heat.

If a force like gravity acts continually on a falling stone in the same direction, the quantity of motion or velocity of the stone continually increases if there be no resistance. But if it be a light raindrop which is falling, the resistance of the air prevents it acquiring great speed, and energy continues to be spent in heating the air and raindrop. If an electromotive force acts continually on a conducting circuit, the current would go on continually increasing were it not for the resistance of the circuit, which prevents the current acquiring great intensity, and energy continues to be spent in heating the conducting circuit.

In all experiments with electric currents we have continual evidence of the transformation of electrical into heat energy. I could not show you a better example than the means of illumination which we have in this room at the present time. In every one of these glow-lamps we have a brilliant illustration of the conversion of electricity into heat. The electrical resistance of these glow-lamps is very large indeed and nearly the whole of the electrical energy which is consumed in the lamps is shown to us by the brilliant light, for I need hardly tell you that heat and light radiations are all absolutely identical except in colour. The glow-lamp consists of a carbon wire bent into a loop. Its two ends are attached to platinum wires which are passed through holes in the glass globe or bulb which contains the carbon wire. These platinum wires form the terminals of the lamp and are attached to the source of electromotive force which we are using, it may be a battery or a dynamo machine. The glass round the platinum is melted round it so as to make an airtight connection. Platinum is used instead of another metal, because after heating the glass and platinum contract to the same extent on cooling. Hence there is no tendency to crack the glass. Copper wires would contract much more than the glass and so they would strain and crack the glass. The glass bulb is exhausted of air by means of a very perfect air-pump. This prevents heat from being wasted in setting up convection currents in the air. It also prevents the wasting of the carbon wire by the friction of the air-currents.



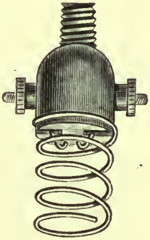


FIG. 15*a*.—Glow-lamp. FIG. 15*b*.—Lamp-holder.

When a lamp has been thus prepared its resistance is generally high. Thus in order to pass a strong current through it we must use a *high* electromotive force. Now we have already found that the electromotive forces of a large and small cell are the same. Thus we can get the high electromotive force required only by multiplying the number of cells in our battery; we cannot do it by increasing the size of our cell. The highest electromotive force of any cell in general use is about 2 volts. With the kind of glow-lamps generally made we require from 25 to 55 such cells.

We have already seen that the resistance of a conductor depends on its length, its section, and its material. It also depends upon the temperature. All the metals become worse conductors when we raise their temperature. All other bodies become better conductors. I believe that this law is universal, and is the most simple definition to distinguish between metals and non-metals. Carbon is a good conductor, almost as good as the metals, but it is not a metal. Its resistance diminishes with increase of temperature.

To illustrate this law with respect to metals, I have here a platinum wire stretched horizontally, and I shall pass an electric current through it so as to make it incandescent. Part of the wire is straight and another part is coiled into a spiral. I shall place a spirit lamp underneath the coiled part, thus increasing the temperature and the resistance. Hence the electric current will be diminished, and what I want you to notice is that the current is diminished as shown by the diminution of glow in the straight part of the wire. I now apply the lamp. You all see how the brightness has diminished in the straight part of the wire. I will now show you the reverse of that effect. I bring a block of ice on to the coiled part of the platinum. This cools it and diminishes the resistance of the circuit. Thus the current increases and you notice that so soon as I apply the ice to the spiral the straight wire shines brighter.

Many of you have followed those researches of philosophers which have laid the foundations of the dynamical theory of heat, a theory which is one of the grandest scientific achievements of the present century. You are aware that the heat in anything consists of a motion of its molecules, and that at a temperature of 273° centigrade below zero all molecules are at rest; there is no heat and we have an absolute zero of temperature. This zero has never been quite reached, but means have lately been devised for lowering the temperature of bodies to within 70° of this absolute zero. Now it is a remarkable fact found from experiment that most of the pure metals have an electrical resistance which is almost exactly proportional to the temperature measured from this absolute zero or 273° centigrade. Experiments have lately been made on the metals at these low temperatures and the resistance has been thus reduced to one quarter of its value at ordinary temperatures, and we have every justification in assuming that the metals at 273° centigrade are perfect conductors of electricity. A current once started in them would go on for ever if no new electromotive force acts. Hence it is very probable that the atoms themselves are perfect conductors, and that the mass owes its resistance in some way to the motions of its parts.

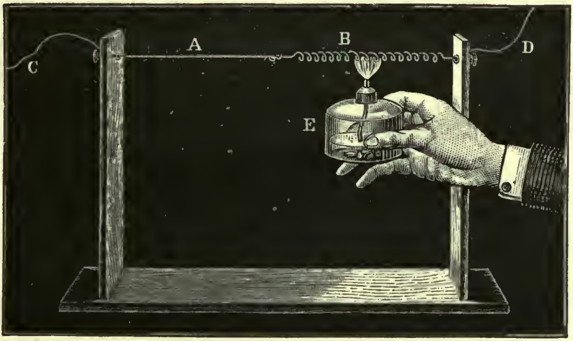


FIG. 16.

A B. Platinum wire. C D. Wires going to battery. E. Spirit lamp. When the lamp is applied, A becomes duller.

I have said that the resistance of non-metals diminishes with increase of temperature. Here I have a long tube with corks in the two ends. It is full of a solution of sulphate of copper. Platinum wires pass through the corks and are connected with a battery. A galvanometer is in circuit to show the strength of the current. You see the index is now about twenty degrees from the position of rest. I now warm the solution with a lamp and you see the deflection of the index increasing; now it nearly reaches the end of the scale. The resistance of the solution has been diminished by heat.

Water on freezing becomes a high-class insulator. Most salts are insulators but become conductors when fused. No substance is known which is a good insulator at a bright red heat.

The arc lamp gives us again a beautiful illustration ot the conversion of electrical energy into heat. It consists essentially of two rods of carbon each connected by a wire with one end of a series of twenty-five cells of a battery. The points of the two carbons are first brought into contact. I have now an image of them thrown on the screen. The current passes and heats the points to redness. They are now separated by a distance of about a twentieth of an inch which is magnified on the screen. The air in contact with the red hot carbons is now heated so as to be a partial conductor. The current passes across this space but experiences considerable resistance. A greater heat is developed, and you see the intense whiteness of the carbon points. The lamp is furnished with an automatic appliance so that when the carbons touch and a current passes, this current is made to separate the carbons by a short space. The oxygen of the air consumes the two poles, but oxygen being a material which attacks a positively electrified body most readily, the carbon connected with the copper of the battery is consumed twice as quickly as the other. The positive carbon is the lowest one on the screen, but the upper one in reality because the image on the screen is inverted. You can also notice on the screen the blue heated air between the carbons. This heated air is a conductor carrying the current. Further you can see particles of carbon being repelled from the positive pole and sticking to the negative one. This transference of electrified particles is equivalent to an electric current. You also see impurities in the carbon, such as silicon, melted into globules. I should like while we have this so beautifully clear on the screen to show you the action of a magnet on an electric current. Mr. Davenport will introduce a magnet close to the luminous arc, and now you can see two things on the screen. You see how the blue heated air carrying the current is deflected into a bow to the left of the carbons. You also see a new behaviour of the positively electrified carbon particles which were moving across from the positive to the negative carbon. I have said that they in their motion are equivalent to a conductor carrying a current and you see that they also are deflected to the left of the carbons. Finally you notice that while the upper or negative carbon is rounded, the lower or positive one is hollowed into a crater owing to the number of particles which fly from it. This part is the position of most vivid white incandescence. The temperature of this crater is the highest temperature that we are able to produce by any means. In this crater, gold, platinum and every solid is melted or evaporated. By placing the salts or oxides of metals in this crater the most refractory substances are decomposed and in this way the valuable metal aluminium can be extracted from its chloride or oxide which can easily be procured, and this is now actually being done on a commercial scale in America.

In the arc lamp as usually constructed the wearing away of the two carbons is compensated by a mechanical feed of the upper carbon alone if the lamp is used only for giving general illumination. When used with the lantern or in lighthouses the light must always be in the optical focus of the condenser lens and both carbons must be advanced, one about twice as quickly as the other if the carbon rods are of equal size. This mechanical feed is started by an electrical action which occurs when the resistance of the air becomes too great by the increased distance between the carbon points.

I will conclude this lecture by showing you that a galvanic cell creates a difference of electric potential. Here is the electrometer which we used in the last lecture, consisting of a freely suspended horizontal needle and four metal quadrants, opposite pairs being connected by wire. I have electrified the suspended needle positively. The first and third quadrants are connected by wire with the zinc of our cell, the second and fourth with the copper. There is no closed conducting circuit and consequently we have no current. But you observe a deflection of the spot of light reflected from a mirror which is supported by the needle. This indicates a motion of the needle when the

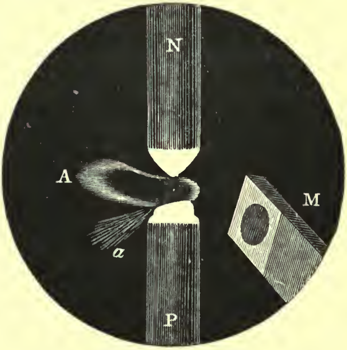


FIG. 17.—Image of arc light.

P. Positive carbon. N. Negative carbon. M. Magnet. A. Heated air. *a*. Carbon particles.

quadrants are connected with the battery, and as you know from the last lecture this means that there is a difference of potential between the wires connected to the two poles of the cell of the same character as the difference of potential which exists between sealing-wax and flannel after being rubbed. I now connect the terminals of the cell by a wire of high resistance. The deflection of the light spot is less, showing a smaller difference of potential between the terminals of the cell. I insert a very small resistance, a short thick wire between the terminals of the cell, and the light spot is hardly at all deflected. The difference of potentials is reduced almost to nothing. I need not tell you that the electromotive force of the battery does not change.

Our unit of resistance is an ohm. Roughly speaking, a tube full of mercury one metre long, and a square millimetre section has an ohm of resistance; a copper wire of the same section and sixty times as long has a resistance of one ohm; a copper wire $\frac{1}{4}$ inch diameter and one mile long is about one ohm. The resistance of the fine carbon wire in these glow lamps is about 130 ohms when incandescent and about twice as much when cold. The resistance of the arc lamp I have been using is equivalent to about 2 to 6 ohms. It varies with the strength of current and with the distance between the carbon points. A mile of telegraph wire (iron) has about nine ohms resistance.

When I have a wire of an ohm resistance and keep its two ends by means of a battery at a difference of potential of one volt there is a current of unit strength in the wire. This unit of current is called an ampère. Each of these glow lamps when fully bright has a current of about $\frac{3}{4}$ of an ampère. The arc lamp has a current varying from 8 to 25 ampères. Telegraph instruments work well with a current of $\frac{1}{1000}$ ampère and even less, 200 ampères of current passing through a copper solution deposit about a pound of copper per hour.

LECTURE III.

MAGNETISM.

I HAVE attempted in two preceding lectures to show you some of the means at our disposal for creating in space that source of energy which we call electromotive force. You have also been able to study some of the different phenomena which are produced according as the electromotive force has or has not a conducting circuit through which it can act. Thus we have begun to be familiar with the thermal and chemical modifications which different parts of a conducting circuit may experience when an electric current is established in it. We have learnt something when we realise that a positive conductor attracts towards it one of the constituents of a chemical compound such as oxygen and chlorine, and that a negative conductor attracts the metallic constituents of liquid solutions. We have gained some steps in our journey when we grasp the fact that the chemical energy used up in a galvanic cell is converted into electrical energy and that the whole of this energy may be reproduced in the form of heat energy in the conducting circuit. We have learnt something when we have been led by experiment to accept the fact that whether the electrification is in a stable condition or whether the electrical strain is being continuously relieved by conduction we have in all cases a manifestation of one single agency acting in obedience to a limited number of very definite laws. The electromotive force established in the space between a piece of glass and silk that have been rubbed together is of the same character as that established between the terminals of a galvanic cell. The discharge of the Wimshurst machine is identical in character with the current from a battery.

To-day we shall spend an hour together among the phenomena of magnetism, and we shall find strong reasons for believing that here also we are dealing only with another manifestation of the same electrical energy. The most complete developments of the theory of magnetism go far to prove that magnetism is due simply and solely to the existence of a large number of small electric currents in the molecules of iron, &c.

The facts in connection with magnetism with which people are best acquainted have relation to terrestrial magnetism. A magnet is generally a bar of steel which has been subjected to a certain process so as to give it properties in addition to those ordinarily possessed by steel. When I balance this steel magnet on a pivot at its middle you see that it takes up a position which roughly speaking is north and south. I disturb it from its position of equilibrium but it always returns to point in the same direction. Natural magnets called lode-stones are often found possessing this property. The metals iron, nickel, cobalt, can be endowed with this property, and the oxides of these metals and a few other substances to a much more limited extent. Magnetic phenomena are chiefly known however in relation to iron and steel. The term steel is applied to iron having a certain quantity of carbon mixed with it. When the proportion of carbon is still greater the material is known by the name cast iron. Nearly pure iron, called wrought iron or malleable iron, is more ductile and pliable than steel or cast iron which are more or less brittle. It is said to be softer and it requires a higher temperature to melt it.

There is another peculiarity about a magnet when freely suspended by its centre of gravity. The end which points to the north also dips downwards at a great angle, about 70° as you see in the case of this magnet, suspended at its centre of gravity, which is free to rotate about a horizontal axis lying east and west. The amount of this dip depends on our geographical position; in higher latitudes it is more nearly vertical, as we approach the equator it lies more nearly horizontal. These phenomena are all due to a magnetic condition of the earth.

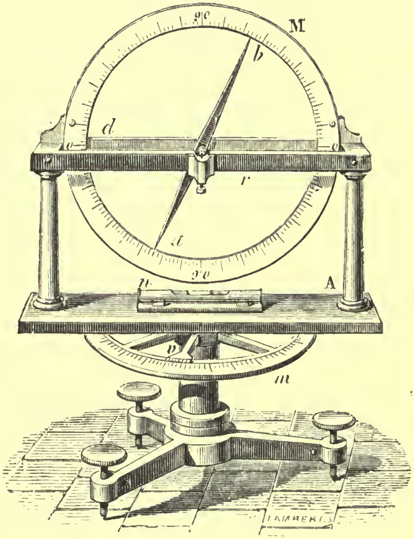


FIG. 1.—Dipping-needle.

The compass-needle does not point exactly north and south in this country, but 20° west of north. This direction is spoken of as the magnetic meridian. The action of the earth on a magnet in this country then tries to put it in a vertical plane inclined 20° to the west of north, and to make it dip at an angle of 70° to the horizon.

I have here two magnets suspended on pivots. I put a white wafer on the north end of each. I now lift one of them off its pivot and bring it near to the other magnet. You see that they exert an influence upon each other. When I bring the north ends together repulsion takes place, the same happens with the south ends, but the north end of one attracts the south end of the other. Those ends of magnets similarly magnetised repel, those that are dissimilarly magnetised attract.

When I place the suspended magnet in different positions with respect to the other magnet it takes up different positions. All the principal phenomena of terrestrial magnetism are explained by supposing a short powerful magnet at the centre of the earth with that end which we call north-seeking pointing to the south and *vice versâ*.

We are never able to find a magnetised body which has only one pole, north- or south-seeking. The two opposite conditions always exist to an equal extent in any magnetised mass. A steel bar, long and thin, retains its magnetisation well, but can lose it when subjected to violent blows. This is the first evidence we detect of a connection between magnetic and purely mechanical actions.

Here I have a long strip of steel, I draw the north end of a magnet along it a few times always stroking it in the same direction. The strip is now magnetised. The end at which I began the stroke is a north end, the other is a south end. You see this when I bring the two ends to the suspended magnet. You might imagine that one half of the steel strip had a tendency to point to the north and the other half to the south. This notion is quickly dispelled. I break my strip of magnetised steel in the middle and each half has now got a north and a south end as you see on testing it. By continuing this we may break up the strip into quite a number of little pieces, but each one has its north and south end. It is not unreasonable to suppose that, if it could be broken so small that we reached the molecule of iron, this also would be a complete magnet with a north and south end. Such a view could not be accepted on such evidence alone, but we shall find many facts all tending to the same conclusion.

According to this view a bar is magnetised when its magnetic molecules all point in the same direction. Conceive a compass-needle placed anywhere in the vicinity of a magnet composed of such molecules all pointing in one direction. The needle is acted upon by the ends of each molecule and one end is generally nearer to it than the other. Repulsion takes place between this end and the similar pole of the needle, and attraction between it and the dissimilar pole. This action of a single molecule is minute, but the result of all the actions of all the molecules will be found to be the same as what at first sight seemed the more likely view, namely, that all the magnetic properties were concentrated in the two ends.

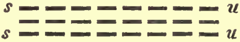


Fig. 2.

A little time ago you saw me make a strip of steel into a magnet by stroking it with the north end of a magnet always in one direction. If this action took place on magnetic molecules it would certainly tend to pull all their south ends in that direction and so to convert it into a magnet. Nevertheless we could never be justified in supposing this turning round of the molecules of iron to be a reality without further proof. I think you will agree with me presently that there are grounds for looking upon this view as being extremely probable. I would not trouble you with these hypothetical views were it not that the conception helps us amazingly in understanding magnetism and no case has yet been discovered where we should be led to erroneous conclusions by adopting it.

Let me give you an illustration by showing you another method of converting a bar of steel into a magnet. We have already found that the earth's magnetism acts in a plane 20° west of north, and dipping at an angle of 70° to the horizon. Here I have a wooden wedge answering these conditions and fixed to the floor. I lay a bar of steel on it so as to lie in the line of the earth's magnetic dip. The earth's magnetism is now trying to move all the magnetic molecules in one direction, but the molecules decline to turn until I now set them into violent motion mechanically by blows from a heavy hammer. The bottom end ought now to be a north end. I bring it near the north end of a suspended magnet and repulsion takes place as we should expect. I will now confirm this proof by reversing the bar on the wedge-stand so that the north end is uppermost. I strike it half-a-dozen times with the hammer, I test it again with the suspended magnet and the end which before was north is now south.

I will now describe to you an experiment by von Beetz which also supports the view of the magnetic nature of iron molecules. Powerful magnets are often made in the shape of a horse-shoe like the one I hold in my hand. The magnetic field between the two poles is very intense. Von Beetz placed such a magnet in the solution of a salt of iron. He then applied an electric current in the manner shown for a copper solution in the last lecture, so that iron was deposited out of the solution on a thin line between the poles. Here each molecule as it was deposited was subjected to a powerful directive force and thus all the molecules were deposited with their axes in the same direction, and a minute magnet was the result, which was more powerful for its size than any which has ever been produced by other means.

I will now read to you the views of Dr. Scoresby about the theory of magnetic molecules, published in 1824. After describing some experiments of his own, he says:—

'All the preceding experiments, it appears to me, tend to illustrate the probable manner of the action of the magnetic particles in a magnetised body, each little magnet made use of being supposed to represent a single particle ; and they, in a particular manner, point out how the individual magnetisms of each particle, when duly arranged, contribute to the total effect. If this be the case, the action of a magnet in developing the magnetic properties of any ferruginous body, simply consists in giving arrangement to the magnetic particles. And the manner in which this is accomplished is, I conceive, very well illustrated by the experiment I shall next describe.

'Let there be several small magnetic needles (those I used were an inch in length) with a small stand of brass for each, holding a fine point, on which the needle may traverse. Arrange them in a row on an east and west line, and at such a distance from each other that, when the needles are in order, and forming a continuous line, their extremities may be about the fiftieth of an inch asunder. In this condition they will be easily arranged (if they do it not spontaneously) in a regular series, with all their north poles one way, when they may be considered as representing the particles of a small magnet, and in a state to afford a striking illustration of the probable manner of action of a strong magnet on a small magnetisable body. For, on passing the north pole of a bar magnet over the series, beginning at the south end of the row, and carrying the magnet at an inch or two elevation above the needles, according to its strength, in a gradual manner, to a little beyond the other end of the series, all the needles will, in succession, turn round, and finally arrange themselves with their poles in the opposite direction to that they had at the commencement. Now, this effect resembles the change of poles produced in a weak magnet, by passing along it the pole of a strong magnet, for in both cases the order of the poles is analogous, the pole where the operation terminates being the reverse of the denomination of the pole passed over. And, in like manner, commencing with the needles in disorder, which resembles the condition of an unmagnetised piece of iron, the mere juxtaposition of one pole of a magnet, or the passing across it of a single pole, arranges the series in a magnetical order, illustrating the development of the previously neutralised magnetic principle. But, besides these resemblances, the principles exhibited by these experiments may be applied to the explanation of the various processes for magnetising iron, and of several phenomena connected with the mysterious agent in question, which have been generally considered as difficult and obscure.'

There is, as I have said, a mechanical difference between steel or cast iron and wrought or soft iron. The former is brittle, the latter ductile. The meaning of this is that in wrought iron the molecules can change their positions more easily than in steel. This property can be shown magnetically. In the neighbourhood of the north end of our suspended magnet I hold an iron poker vertically. This poker is made of wrought iron. It is subjected to the magnetic force of the earth and all its molecules turn with their north ends downwards. The consequence is as you see that the point of the poker which is downwards is a north end and repels the north end of the magnet, while the handle attracts it. The handle then while at the top is a south pole; and this result is produced without any of the blows required by the steel. Now I will show you a remarkable experiment. The handle being uppermost now attracts the north end of the magnet. I keep the handle at the same point of space but invert the poker, and you see repulsion take place. This shows that the soft iron molecules move freely in obedience to the earth's magnetism and the lower end is always the north end. This does not happen with a hard brittle rod of cast iron. You see that there is a slight attraction shown by this end of it, whether it be the upper or the lower end. I will finally give both the poker and the cast iron bar a violent blow with a heavy hammer, and you will observe the mechanical effect. There, you see that the poker is but showing that its molecules can freely change their relative positions. It is twisted. Now let us try the bar of cast iron. You see it is broken by the blow. The molecules are not free to change their positions.

You have just seen that a piece of iron or steel when placed in a magnetic field, that is, a part of space subject to magnetic influence, can be converted into a magnet.

The soft iron is thus easily magnetised and loses its magnetism when it is removed from the magnetic field.

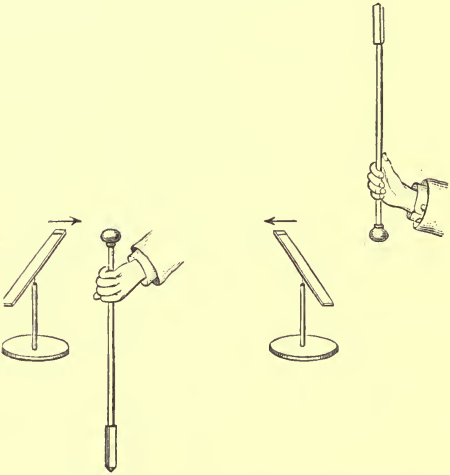


FIG. 3.—Attraction of a north pole by the upper, and repulsion by the lower end of a soft iron poker.

Steel requires mechanical blows to be fully acted on by a change of magnetic field.

The magnetic field which was used in these experiments was that due to terrestrial magnetism; but we have the means of producing far more powerful fields than that. It is found that when an insulated wire is coiled into the form of a hollow cylinder, an intense magnetic field is produced in the inside of the cylinder when an electric current is established in the wire of the cylindrical coil.

Here I have such a cylinder and a battery of galvanic cells which will enable me to get a powerful electric current. An iron poker is placed inside the cylinder; its end has no attraction, as you see, for the large nails I have in my hand. I now establish a current in the wire of the cylinder. The poker is now intensely magnetised. You see it supports iron nails at its ends.

This experiment suggests a natural question. Why does a magnet attract an iron nail and give to it the power of attracting others? The answer is not difficult. The magnetised poker creates a magnetic field in its neighbourhood. When a nail is placed there it becomes magnetised with a north and a south end. The north pole of the magnet attracts the south of the nail, and *vice versâ*. So soon as the nail touches the end of the poker it is in a much stronger field than before, and becomes so strongly magnetised that it can in turn support other nails, and so on. This is the simple reason why a magnet attracts a piece of iron. It first magnetises it by induction, and then the two magnets act upon each other in the usual manner.

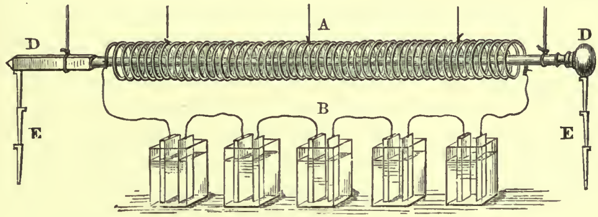


FIG. 4.

A. Hollow cylinder of insulated wire wound in many turns. B. A battery of galvanic cells. D. An iron poker. E E. Horse-shoe nails supported by the poker when a current flows in the wire.

When we convert a piece of iron into a magnet by placing it, as I have seen done, in a magnetic field produced by an electric current, we say that the iron is an electro-magnet. This power that we possess of giving to iron or taking from it the magnetic property, simply by completing or breaking the conducting circuit from a battery, is one of the greatest practical importance, and it cannot be without interest to understand this action a little more fully. Here I have a powerful electromagnet made of the softest annealed iron. The iron is shaped like the letter U. Its section is about two inches, and the length of each arm is about 10 inches; it is coiled with insulated copper wire. I have also a flat piece of iron with a handle. I lay it over the poles of the electromagnet, and you see there is no attraction whatever; it is not magnetised at all, but so soon as I connect the ends of the copper wire with the terminals of an electric battery, you see that it is attracted with great force. At this moment the flat iron keeper (as it is called) rests only on one pole, and you see that I must exert considerable effort to pull it away. I disconnect the battery and the keeper falls off. The magnetic condition has disappeared. Now I alter the experiment by placing the keeper over both poles; passing the electric current through the copper wire the force of attraction is now enormously greater. I cannot pull the keeper from the magnet when exerting my utmost strength. The electric current exerts a definite power trying to magnetise a magnetically conducting circuit which offers some resistance to being magnetised. If we have a complete iron circuit, as in the last experiment, the resistance to magnetisation is small and the magnetisation is enormous. In the first experiment the magnetic circuit was composed partly of air, which offers great resistance to magnetisation, and so we had much feebler magnetisation. This resembles closely the phenomena of an electric circuit. A battery exerts a power trying to set up a current. The conducting circuit offers some resistance, and the current is stronger in proportion as the resistance is less. There is this difference however. The electric circuit can be broken and the parts separated by an insulator, in which case no current passes. There is no such thing as a good insulator of magnetism; all materials except iron, nickel, and cobalt are bad magnetic conductors, but the worst of them is only two or three thousand times worse than the best iron. Whereas among electric conductors, if we exclude the metals and carbon, all other materials are millions of times worse conductors, and many are billions of billions of times worse than copper or silver.

Our electromagnet is now holding the keeper firmly attached. I remember some fourteen years ago when I was showing this electromagnet, which was a new acquisition, to the students in my class at Glasgow, I told them that on breaking the electric circuit the magnetism would disappear. I proceeded to do so, but the keeper was held on with enormous force. This was my first acquaintance with what has since been called magnetic hysteresis. The phenomenon is most marked when as in this case we have a complete circuit of magnetically conducting material like soft iron. It is then found that the influence of a magnetising force is not lost on the cessation of that force, but here again is a remarkable fact confirming what I have said about the molecular theory of magnetism. I have

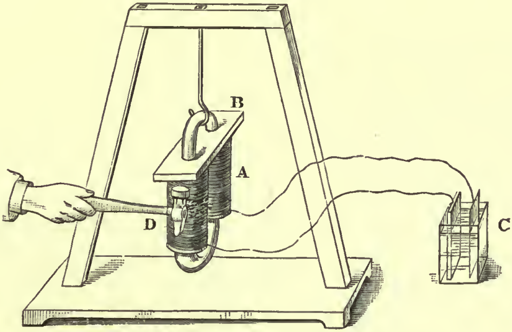


FIG. 5.—Magnetic hysteresis.

A. Electromagnet. B. Keeper. C. Battery which has magnetised the iron, but is now discounted. D. Hammer. On tapping the magnet it falls from the keeper.

now got the whole weight of the magnet supported by the keeper, although no electric current is passing in the coils. I tap the magnet gently with a hammer to set its molecules into mechanical vibration, and you see the magnetism disappears and the magnet falls from the keeper.

People have often tried to make stronger magnets by taking a bar of iron, surrounding it with coils, surrounding the coils by an iron tube, connecting the lower ends of tube and bar with iron, and causing the keeper to touch the top surface of both bar and tube. The object was to utilise the magnetising power supposed to exist outside the coils. These people have failed because the magnetic power of a long coil of wire carrying an electric current is exerted almost entirely on its inside.

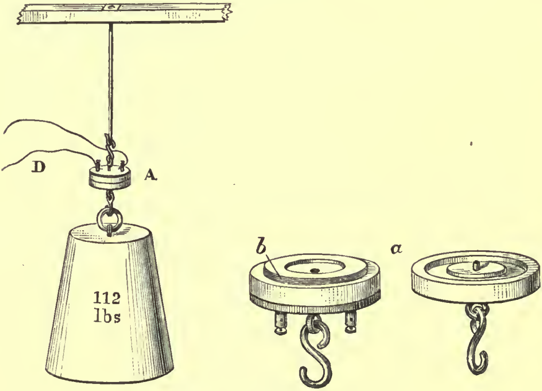


Fig. 6.

A. Electromagnet. *a*. The same in two pieces; *b*. Coil of wire.
D. Wires going to battery.

If the attempt had been made with a short coil it would have been quite successful. I have suspended over my head such an electromagnet which consists merely of two flat discs of iron with a circular groove between them, in which a coil of fine insulated copper wire lies. I pass an electric current through it and see what a weight it can support. When we look at the small size of the magnet weighing about three ounces, and the considerable weight, over one hundred pounds, which it supports we can appreciate its great power. It is the most powerful magnet for its size that could be constructed.

I may now give you another illustration of hysteresis which came under my notice in January 1883. The model dynamo machine before you consists of a cylindrical bar of soft iron to which I can give rapid rotation about its axis. It has two coils of wire round it with a vacant space between them at the middle of the bar. The coils are surrounded by a soft iron cylinder which makes a complete circuit of good magnetically conducting material. I pass a current through the wire coils and rotate the iron bar. Now, by touching the rotating bar with two ends of a wire, at one end and at the middle of the bar (a hole being made in the outer iron cylinder for this purpose), an electric current is established in the wire as you see indicated by the galvanometer. Now I break the electric circuit, but the galvanometer indicates no sensible diminution of the current. Now here, as in all dynamo machines, the current depends on the intensity of magnetism, and this experiment shows that even after the magnetising force is removed the magnetism remains if we have a complete magnetic circuit of soft iron.

The coil of insulated wire of cylindrical form which I have shown to you is a convenient means of obtaining a magnetic field whose strength can be varied by varying the electric current in the coil. We can put an iron rod into the cylinder, and as we increase the magnetising force we can observe the intensity of magnetisation by observing what deflection of a compass-needle is produced by one of the ends of the bar, or by observing the weight of iron which can be supported by an end of the bar. In this way it has been found that with feeble currents an increase in electric current produces a corresponding increase in magnetisation, but that this increase of magnetism is less marked as the electric current is stronger, and it looks very like as if there is a limit of magnetisation never attained in practice which could not be exceeded even with an infinite magnetising force.[1] According to the molecular hypothesis this state would be attained when all the molecules point in the same direction. Be this as it may, it is certain that after we have applied a certain magnetising force (whose amount depends upon the quality of the iron) the iron is practically *saturated* (as we say) with magnetism. This is equivalent to saying that the magnetic resistance of iron is not constant but increases with the intensity of its magnetisation. With a considerable magnetisation the resistance becomes very great indeed. Different pieces of iron and steel vary considerably both in their resistance and in the variation of resistance when the magnetism is increased. The magnetic resistance of iron wire is largely increased by stretching it. Here again we have another connection between the mechanical and magnetical forces exhibited by iron. Professor Hughes has given a striking instance of this connection. Here is a strip of soft hoop iron. I draw it over the north pole of a magnet. I bring it near the suspended bar magnet neither of whose ends is repelled. The iron strip is not magnetised except while under the influence of a magnet. I now bend it like a bow and so put its molecules into a state of strain. I again draw it over the north pole of a magnet. I bring it still strained near the suspended magnet and the two ends of the strip show repulsion and attraction on the two ends of the suspended magnet. The soft iron retains magnetism like hard steel when its molecules are definitely set by a mechanical strain.

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[1] The later experiments of Ewing and Shelford Bidwell throw some doubt on this point.

When Faraday was engaged in his brilliant researches on magnetism he was accustomed to study the nature of magnetic induction and its direction in space by means of iron filings. I have here a small horse-shoe magnet fastened beneath a horizontal sheet of glass—an image of which by the aid of the lantern and a suitable arrangement of mirrors I can project upon the white screen on the wall. I now sprinkle iron filings from a muslin bag upon the glass, and you will see the direction in which they lie, after I shake the glass. Each little piece of iron is by the power of the horse-shoe magnet converted temporarily into a little magnet, and settles itself in that direction in which the magnetic influence of the horse-shoe is acting at that point in space, and then the filings form strings of little magnets end to end along the line of induction. You see distinctly now those beautiful curves connecting the poles which come out more clearly when I tap the glass gently so as to allow the filings to settle in their proper directions. Now you will observe that there is always a tendency for the lines of filings to go from one end of the horse-shoe to the other. There is comparatively little magnetic power exhibited at other parts of the magnet but only at its ends. Again if you will think for a moment on the molecular hypothesis which I have sketched for you, these lines of

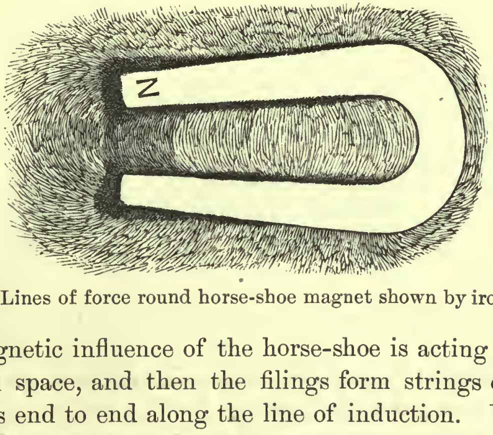

FIG. 7.—Lines of force round horse-shoe magnet shown by iron filings.

magnetic filings will appear to you simply as a continuation of the lines of molecules supposed to lie end to end in the interior of the magnet. Faraday supposed that even in space which we consider to be empty, magnetic induction is propagated from point to point of the ether along these lines of induction. He spoke of them as lines of magnetic force or magnetic lines of force. According to his view each string of molecules, placed end to end in a magnetised bar, when it reaches the surface of the bar, is still continued through space as a line of force, so that his lines of force are closed curves.

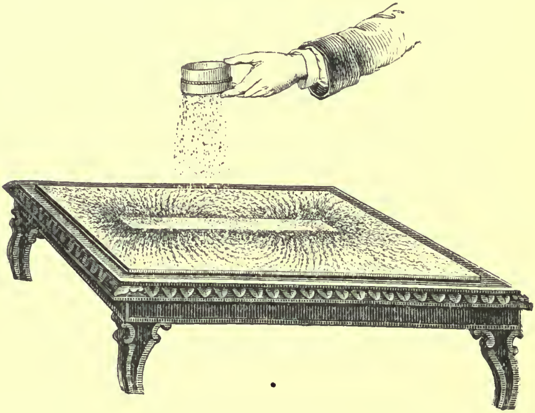

FIG. 8.—Lines of force round bar-magnet shown by iron filings.

Here I have the horse-shoe replaced by a straight bar magnet. The lines of force go from pole to pole and show the direction of the magnetic induction.

A consideration of these lines of force helps us not only to understand magnetism but also to group into comprehensive laws a host of electro-magnetic phenomena which will be examined in another lecture.

Faraday in his philosophical researches was continually led by electrical and magnetical phenomena to a belief in the existence of an all-pervading ether, such as had been already demanded by the theory of light. You have already seen in the first of these lectures he was led, probably by considering the different velocities with which light is propagated in different media, to expect and to prove that electrical induction also depended upon the medium through which it acted, thus establishing a kind of similarity between the ether demanded by the theory of light and that demanded by electrical theory. Clerk Maxwell, in his *magnum opus*, which had for its aim the working out of Faraday's views into a complete and mathematically quantitative theory, went so far as to propose an electro-magnetic theory of light, the most startling evidence in favour of which is that the velocity with which electrical induction takes place through empty space is the same as that with which light is propagated, 300,000 kilometres per second.

But Faraday, when he came to see that magnetic induction involved the existence of an ether, attempted to find some connection between light and magnetism which would make it probable that the same ether plays the double part for magnetism and for light. He succeeded in establishing a connection so startling that even now his experiment stands out among all magnetic phenomena as being incomparably the most wonderful in the whole of this branch of physical science. It is only an experimentalist who can realise the long series of preliminary unsuccessful experiments, the hopes and disappointments of years of laborious research (true philosophical research in its best signification), it is only he who can appreciate the undying faith of this great man's mind in the unity of the physical forces which led him on, undaunted in spite of failures which only served to excite him to new effort, to the final success in an experiment which was as bold in its conception as it was unequivocal in its indications.

To show you this experiment I use the lantern and the same Nicol's prisms which I used in the first lecture. The prisms are placed in one line and the lantern sends a beam of light through them to the screen where now you see a round white spot of light. Both the prisms are now placed so that they allow only the vertical vibrations of the ether which are the cause of luminous radiation to pass through them. I turn the second prism through 90° round the beam of light as an axis. Now the vibrations transmitted by the first prism are all vertical, and the second prism allows only horizontal vibrations to pass. Thus no light can pass through both prisms and you have darkness on the screen. You see that if I could change the direction of vibration of the light which has passed through the first prism before it reaches the second one then some light would pass through the second one. To produce darkness it would then be necessary to turn the second prism through a small angle about the ray of light as an axis.

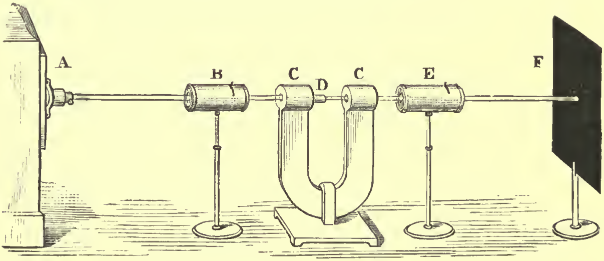

FIG. 9.

A. Lantern. B. First Nicol's prism. C. Electromagnet. D. Dense glass.
E. Second Nicol's prism. F. Screen.

Between the two prisms I place a U-shaped electromagnet, with a hole through each pole, these holes being in one line, so that the beam of light can pass through the holes. Between the holes I place a piece of very dense glass which shows the effect better than any other material. At the present moment the glass is not in a magnetic field because no current is passing round the electromagnet. All the light which passes through the first prism is cut off by the other, and the screen is dark. I now create a magnetic field, where the glass is, by connecting the electromagnet with a battery, and instantly you see light upon the screen. I turn the second prism through a small angle and again we have darkness. By magnetising the space occupied by the glass, the direction of the ether's vibrations which constitute radiation has been rotated. This is a startling result which confirms us in our belief in the existence of that ether demanded equally by the theory of light as well as by electrical and magnetical research, and which goes far to prove an identity among those physical energies which seem by their ordinary effects to be totally distinct. This rotation of the direction of vibration of the ether during its propagation through a transparent substance was not new. If the magnetised glass be replaced by quartz so cut that the beam of light passes along its crystallographic axis, a similar illumination of the screen is produced, due to a rotation of the direction of vibration. But there is a notable difference between the two. In using magnetised glass it does not matter in which direction the beam passes; the rotation is always in the same direction, namely, in the direction in which the hands of a watch would rotate if the face of the watch were towards the north pole of the magnet which produces the magnetic field. In using quartz instead of magnetised glass the direction of rotation is different in the two cases. If the beam after passing through the quartz is reflected back, the rotation is cancelled; with the magnetised glass it is doubled. Some substances when magnetised rotate the direction of vibration in one direction, others in the opposite direction. In a film of iron thin enough to be transparent the effect is very strong. The experiment proves rotation of the ether or of the molecules in the interior of magnetised bodies.

We have now seen many connections between magnetic phenomena and purely mechanical motions; but, even at the risk of tiring you with the subject, I must draw your attention to another class of phenomena attendant upon the magnetisation of iron which was first discovered by Joule. He proved that when an iron bar is magnetised

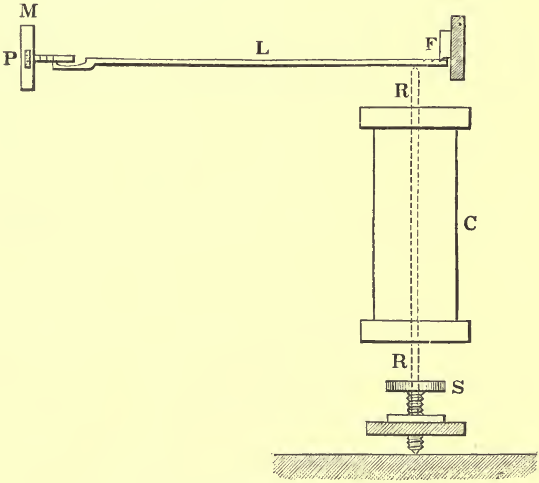

FIG. 10.—Bidwell's apparatus.

C is a coil of wire, R an iron rod working the lever, L, which has a fulcrum, F. The lengthening or shortening of the rod R is shown by the movements of a spot of light reflected from the mirror, M, on a pivot, P.

its length is increased. It has been supposed by some that the cause is to be found in a greater length of the molecule of iron along its magnetic axis, so that when all the molecules are twisted so that their lengths all point one way the bar is lengthened. This view is rather weakened by the subsequent discovery of Mr. Shelford Bidwell, who has confirmed Joule's discovery so far as moderate magnetisation is concerned. But he finds that when the magnetisation is increased the bar ceases to expand, diminishes to its natural length, and with very powerful magnetising forces actually contracts to a considerable extent. As to the causes of these phenomena we are in darkness. But I feel confident that they are bound to tell us a great deal about the true physical meaning of magnetism.

I consider myself fortunate in being able to show you with Mr. Bidwell's assistance the results which he has obtained. The apparatus used by him consists of a piece of iron rod fixed at the lower end, but pressing upwards on a lever. The long arm of that lever acts upon a mirror resting on a pivot, so that if the iron rod lengthens it turns the mirror about a horizontal axis. The lime-light in the lantern throws a beam of light upon the mirror which is reflected from it, and after crossing the whole length of this room strikes a scale on the wall. If the iron bar shortens the spot of light will rise on the wall, if it lengthens the light-spot will sink. I commence now with a feeble magnetising power. On the scale you see a black line crossing the spot of light. It is the image of a wire in the lantern, and by watching it you will know whether the iron lengthens or contracts. The iron rod is contained in a helix of insulated copper wire, through which I now pass a feeble electric current. Now the iron is feebly magnetised, you see a descent of the black line on the scale, indicating that the iron has expanded in length. The motion of the line is about 1½ inches. I now ask Mr. Bidwell to increase the electric current and so produce a very intense magnetisation. There, you see the line rising, indicating a very considerable contraction of the iron rod.

Finally, as we have this experiment arranged, I will show you the effect upon another magnetic metal—nickel. Here you notice that even with feeble currents we always have contraction, and the contraction is far greater than what we obtained with iron. The contraction is indicated by a rise of several inches upon the scale. This really means a very small change in the length of the rod, because the means adopted for magnifying the motion are so powerful.

I do not think I would have said so much about the molecular hypothesis of magnetism were it not the means of deducing all magnetic phenomena from a consideration of the mutual action of electric currents. In the next lecture we shall learn the manner in which conducting circuits which carry electric currents act upon each other.

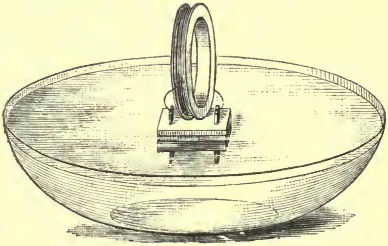

FIG. 11.

At present I will content myself with showing you an enlarged representation of what the magnetic molecule is supposed to be. It results from the researches of Ampère that a circular electric current acts like a magnet. If we can suppose the material of which an iron molecule is composed to be a perfect conductor of electricity, then an electric current once started in it would go on for ever. According to this view the molecules of iron were created with electric currents in them, which exist now and will exist for ever. You must surely have been struck by the facility with which magnetic phenomena are accounted for by supposing the molecule of iron to be a little magnet; but it may have seemed to you like shifting the difficulty back a step for is it not as difficult to explain the magnetism of the molecule as of the mass? Once we see that the magnetic properties of the molecule are explicable by well-known agencies, the atmosphere becomes clearer and we are one step nearer to an explanation of the unity of the physical forces.

I will now show you that a circular current acts like a magnet. Here I have a coil of wire the two ends of which are attached, one to a piece of copper, the other to a piece of zinc. These pass through a cork which floats upon acidulated water in this glass-dish (fig.11). A current of electricity is thus established in the coils. You notice that the axis of the coil rests in the magnetic meridian. It points approximately north and south. I can give you further proof that this current of electricity acts like a magnet. I bring near it an ordinary steel magnet and you see that the coil is deflected. Using the north end of the steel magnet it attracts one face of the coil and repels the other so as to send it right across the dish.

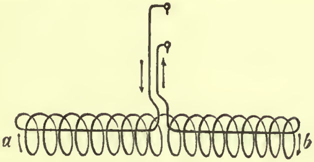

FIG. 12.

The south end of the steel magnet acts in the opposite way upon the circular electric current.

Here again I have a helix of insulated copper wire making a long cylinder (fig. 12), which is equivalent in its action to a great number of circular currents with all their axes in the same line. This then represents a string of magnetic molecules all pointing in the same direction, as when a bar of iron is magnetised. The helix is suspended at its middle by two thin wires connected with a battery. A current is now passing through each coil of the helix which sets its axis in the magnetic meridian and which as you see I can influence by a magnet exactly as if it were a magnet itself.

The high temperature of a body is known to be due to a violent motion or oscillation of its molecules and it is not unreasonable to suppose that the magnetic character of iron and steel should be affected by a high temperature. We find that this is actually the case. Here I have two iron balls similar in every respect except that one is cold and the other nearly white hot. I bring them in turn towards one end of a suspended magnet. Attraction takes place with the cold ball, but there is absolutely no effect with the hot one. It cannot be magnetised.

Two equal magnets are said to have poles of unit strength if two poles attract or repel each other with unit force at unit distance. This unit of magnetic strength is rather small if we take the centimetre, gramme, and second as our units of length, mass, and time. Here I have two equal steel magnets, one of which is hung to an arm of a balance and weighed with and without the action of a pole of the other magnet increasing its weight. The magnets are each 18 inches long and the magnetic strength of the poles is 200 units. We have also got a unit for denoting the strength of a magnetic field. The strength of the magnetic field produced by terrestrial magnetism in this room is about ·46. The strength of field produced by powerful dynamo machines is about 10,000 or 20,000 units. The field of greatest strength yet obtained is 48,000 units. The greatest weight which a magnet has been made to support is about 200 lbs. per square inch.

When bisulphide of carbon is placed in a magnetic field of strength 10,000 units, each centimetre measured along the lines of force turns the plane of vibration of the ether through an angle of about 60°.

The magnetism of iron ships interferes materially with the action of the compass in indicating the magnetic north. This magnetism is never so great in its effect as terrestrial magnetism if the position of the compass on the ship be well chosen. Suppose the iron ship to act on the whole like a steel magnet with its north-seeking end at the bows. When the ship's head points north the magnetic poles at the bow and stern tend only to weaken the directive force of the earth's magnetism; they do not produce any error in the direction of the compass. When the ship's head points south these poles strengthen the earth's directive force and again produce no error. When the ship's head points east, the compass points to the west of north. When the ship's head points west, the compass points to the east of north. These errors can be compensated by placing a magnet on the deck with its south-seeking end towards the north, to counteract the ship's permanent magnetism along its length.

Suppose part of the ship's magnetism arises from longitudinal pieces of soft iron lying along the length of the ship, these are magnetised only by induction from the earth's magnetism. They are most powerfully magnetised when the ship's head is north or south, but produce then no error on the compass. They are not magnetised when the ship heads to the east or west. Thus at the cardinal points, N, E, S, W, they produce no error. They produce the maximum error when the ship heads to the quadrantal points, NE, SE, SW, NW. These errors can be compensated by balls of soft iron placed on the port and starboard sides of the compass.

These are the principal causes of error, but in some cases greater refinements are required. A vertical bar of soft iron acts like a permanent magnet whose intensity varies with the latitude. In the northern hemisphere its upper end is a south pole. In the southern hemisphere it is a north pole.

LECTURE IV.

ELECTRO-MAGNETISM.

In a previous lecture when the phenomena of the electric current were before us we saw various means by which an electric current could be started in a conducting circuit. We also saw something of the effects which are produced by such electric currents. It will be my endeavour to-day to show you experiments illustrative of the grand discoveries which were made during the third decade of the present century. During that period were established the connections between magnetism and electricity. This department of the Science is called electro-magnetism. The chief discoverers in the realm of electro-magnetism were Oersted, Faraday, Ampère, Sturgeon, Page and Henry.

Previous to the year 1819 there were but few effects of the electric current known to philosophers. The means at our command for detecting the existence of an electric current in a wire were few. It was known that heat is generated in a conductor through which an electric current is passing. It was known that a spark could be obtained from two charcoal points through which an electric current passes. It was further known that chemical substances could be decomposed, and that water could be reduced to its constituent elements of oxygen and hydrogen gas, when an electric current passes through it. These, however, were almost the only means of detecting the existence of an electric current in a wire. The only electric telegraph in existence at that date was constructed by carrying twenty-six wires representing the twenty-six letters of the alphabet. At the sending station electric currents were sent through the different wires in succession so as to spell out the words. At the receiving end the existence of these currents was made evident by the decomposition of water, bubbles of gas being given off from the wire corresponding to any letter of the alphabet indicated by the sender of the message. This was Soemering's telegraph, which was never commercially used. A successful telegraph was then an impossibility, owing to the limited means at the disposal of the inventor for the detection of an electric current in a wire.

Even at the end of last century, however, there was evidence of some unknown kind of connection between electric phenomena and magnetism. A certain number of facts, isolated and non-reproducible, had been collected, affording a prevision of what was to come. During a thunderstorm at sea it had been not unfrequently noticed that when a vessel was struck by lightning, the compass needle was rendered useless and would sometimes point in a direction exactly opposite to that in which it would set previous to the lightning flash.

But it was not until the year 1819 that the key was found to this mysterious half-suspected connection between electricity and magnetism. In the year 1883 there was a magnificent exhibition of electric apparatus at Vienna; and I well remember how after wandering over that enormous building in the Prater and admiring the developments of the science displayed in connection with telegraphy, telephony, electric lighting and transmission of power, electric clocks and all kinds of electric appliances, I came in a secluded spot upon a small exhibit which held me bound by a feeling of respect, almost of awe, as I thought how much the progress of the world had been affected by this small instrument. The exhibit consisted of nothing more than a compass needle placed on a velvet stand with a glass shade over it and watched over by a bust of the illustrious philosopher who had used it. The compass needle and the bust were those of Professor Oersted, of Copenhagen; and his experiment with this instrument was the seed which grew and produced the galvanometer, the electro-magnet, the electric telegraph and telephone, the dynamo machine, electric motors, electric clocks, and nearly all the electric appliances exhibited in that great building. It laid the foundation of the science of electro-magnetism, and I think that you and I shall be able to see this afternoon, as we take up one experiment after another, how it might have been possible almost to have foretold from that one experiment most of the later discoveries which now form the foundations of our science.

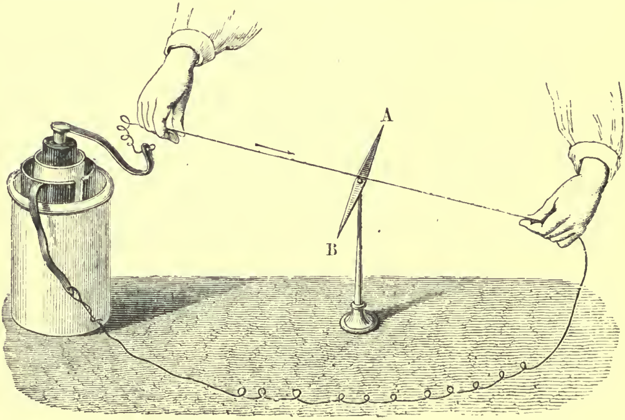

FIG. 1.

An electric current flowing from the copper of a voltaic cell over a compass needle from south to north deflects the north end of the needle to the west.

I will now show you Oersted's experiment.

You see that I have a long wire connecting the copper and zinc of this voltaic cell. We know that an electric current is passing through it, from the copper through the wire to the zinc. I now stretch out a portion of this wire and hold it over a compass needle so that the current goes from south to north (fig. 1). You see the north end of the needle is deflected to the west, and the south end to the east. I reverse the direction of the current and a reverse deflection takes place. This test for the presence of an electric current is more useful than one depending on the heating of the wire. It tells us not only when a current is passing, but also in which direction it is flowing.

Any one with clear notions about the geometry of position could now foretell that on holding the wire under the needle instead of over it the direction of deflection of the needle will be reversed. We will try the experiment. I hold the wire over the needle, the north end is deflected to the west. I hold it below, it now goes to the east. If I give the wire a turn round the compass needle so that the current flows over the needle from south to north and under it from north to south, the two actions reinforce each other, both turning the north end of the needle to the west. If I repeat the operation by making a number of turns of wire surround the compass needle (fig. 2), I multiply the effect, provided I take care that successive turns of wire are insulated from each other, which is done by covering the wire with cotton, or better, with silk, or even gutta percha or indiarubber. By this device the current

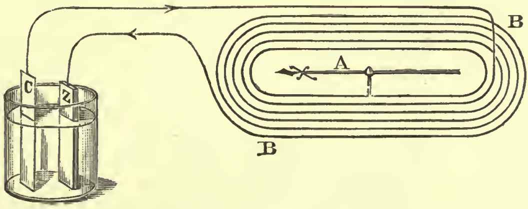

FIG. 2. – Galvanometer.

A. Compass needle. B. Coils of wire. An electric current flowing with the arrows deflects the north end of the needle (marked with a cross) to the east.

cannot take a short cut from one turn of wire to another, but must go round each turn completely. Thus we obtain a galvanometer which enables us to detect the presence of very feeble currents.

Now you will notice that if we wish to state the general law about the action of currents and magnets, we must not define the action as being dependent upon the position of the current above or below the needle. Clearly the action would take place if the current be at one side of the needle. Here I have a dipping needle. I hold a wire carrying a current parallel to the needle and you see that it is deflected (fig. 3).

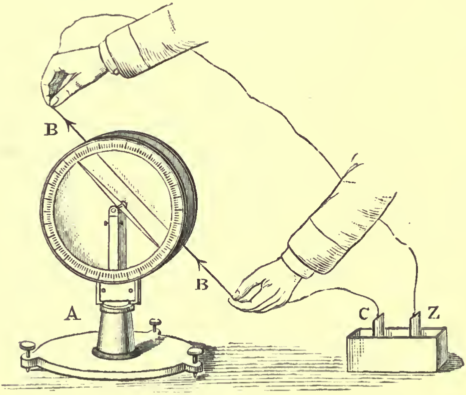

FIG. 3.

A. Dipping needle. B B. A wire west of needle with current flowing from its north to its south end. The north end moves upwards, the south end downwards.

This action is a curious one, almost unique in nature. The mutual influence of the current and a magnetic pole is not one of attraction or repulsion. The north or south pole of the needle is not moved in the line joining that pole to the electric current, but at right angles to that direction. Nor, again, is the action parallel to the flow of the current, but at right angles to it. When we consider the action of a small straight bit of the electric current on a magnetic pole beside it, there are three lines at right angles—namely, the line joining the bit of current to the magnetic pole, the line along which the current flows, and the line along which the magnetic pole tends to move. Stretch the thumb of your right hand away from your fingers. Place your hand on the wire carrying the current, with the palm facing the north pole of the magnet and the fingers pointing in the direction the current flows; then your thumb indicates the direction in which the north pole tends to move. The south pole tends to move in the opposite direction.

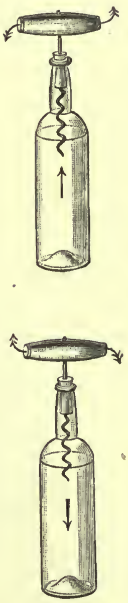

FIG. 4.

If a current flows in the direction of the single arrow a north pole tends to rotate round it in the direction of the double arrow.

If an ordinary corkscrew be twisted to the right it moves at the same time through the cork into the bottle; if it be twisted to the left it has a linear movement in the opposite direction. Lay your corkscrew, or imagine it laid, so as to lie along the wire carrying the current. Twist it so that it moves in the direction of the current flowing along the wire; then the handle turns in the direction in which a north pole is impelled (fig. 4).

If you imagine yourself laid along the wire, the current coming in at your feet and going out at your head, so that you swim with the current, and if you face the magnet you will see the north pole go to your left and the south pole go to your right.

Any one of these three rules will suffice for all cases that can occur. I would recommend the second rule in preference to the others if you happen to know which way a corkscrew turns.

You will easily see now that each pole of a magnet tries to go round a wire carrying an electric current. If the magnet were quite flexible it would wrap itself round the current. But it is rigid and cannot do this, and its rigidity only allows it to try to set itself at right angles to the current. If we could find a magnet with only one pole it would if free move continuously round and round a current-carrying wire. This is impossible, for we cannot find a north pole mechanically dissociated from a south pole. We may, however, obtain this continuous rotation by a special device. We can arrange matters so that the current acts only on one of the poles. Here I have a magnet doubly bent at its middle (fig. 5). Through this middle part a stout wire passes, going the whole length of the magnet and pivoted at its two ends, the magnet

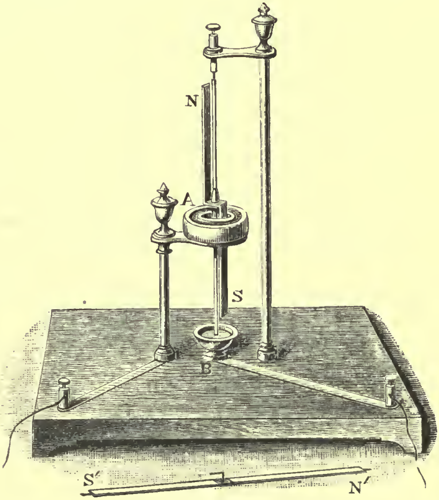

FIG. 5.

The current descends from the mercury ring, A, to the mercury cup, B. The south pole is alone acted upon.

and wire being vertical. If a current were passed along the whole length of this wire, the north and south poles would tend to go round the current in opposite directions and no rotation would ensue. To prevent this the current which is admitted through the upper pivot of the stout wire leaves it at the middle of the magnet by passing through a horizontal wire there soldered to it, and bent down so as to dip into a ring trough of mercury. Mercury is a good electric conductor, and a wire fixed to the trough and dipping in the mercury is led to the zinc of our voltaic cell and completes the circuit. The upper pivot of the wire has a mercury cup to make good electric contact. The current now leaves the copper of the voltaic cell, enters the stout wire at its upper pivot, passes beside the north pole of the magnet (if that one be uppermost), deflecting it in the way a corkscrew handle turns when going down into a cork. The current leaves the stout wire at its middle, going by the mercury ring trough through the fixed wire to the zinc of the voltaic cell. The current has never approached the lower pole of the magnet. It follows that if our logic is right, Oersted's experiment makes us certain that if the strength of the magnet and of the current be

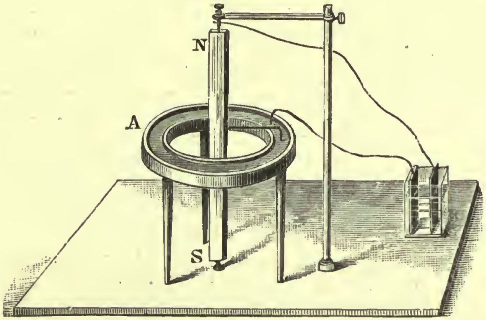

FIG. 6.

N S. Bar magnet pivoted at top and bottom. A. Mercury ring.

sufficient, and if the mechanical friction be small, we must get rotation of the magnet continuously round the wire carrying the current. I now make contact with the battery and you see that our anticipations are realised. I now reverse the direction of the current and the magnet rotates in the opposite direction.

Here again is another similar, but perhaps more striking, arrangement of the same experiment (fig. 6). Here I have a magnet without any wire. The magnet itself is pivoted at top and bottom. A wire is attached to the middle of the magnet, dipping as before into a ring mercury trough. The current enters at the top of the magnet and leaves it at the middle without ever approaching the lower pole, and you see that we get continuous rotation as before. These continuous rotations of a magnet pole round a current were first produced by Faraday. It is interesting to see how we could by a mere consideration of the geometries of place and motion deduce these effects with certainty from Oersted's experiment.

We now know that a current produces in its neighbourhood a magnetic field, as it is called. I mean that a compass needle near an electric current has just as much a tendency to set itself in a definite direction as if it were subjected to the direct action of a magnet. There can be no difference in the character of the magnetic field produced by a magnet and the magnetic field produced by an electric current. Both are able to give direction to a compass needle; and if a magnetic field produced in one of these ways can produce other effects, we may be quite sure that the same effects can be obtained from the magnetic field produced by the other method. Now a magnetic field produced by a magnet not only gives direction to a compass needle, but it induces magnetism in a piece of soft wrought iron; and having done so it can exert an attractive as distinguished from a merely directive action. Thus we may be very certain that an electric current can magnetise a piece of soft iron, and then attract it.

Before convincing you by experiment of the justness of our logic, I will offer some suggestions which may lead us to arrange our electric current so as to get a somewhat powerful effect when we make the experiment.

If I have an electric current going round in a ring you will notice that by the rule we have obtained every bit of the ring carrying the current is trying to drive the north pole of a magnet through the middle of the ring in one direction, and the south pole in the opposite direction. So that if a compass needle were suspended in the centre of the ring it would have a strong tendency to set with its length along the axis of the ring. Now if I replace the ring in which a very strong current passes by a coil of 1,000 turns of wire the current will only require to be one-thousandth of the strength to produce the same effect. Now such a coil and compass needle combine to form the galvanometer for measuring small currents which we lately considered.

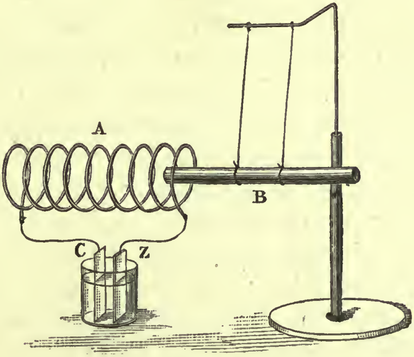

FIG. 7.

A is a coil connected with battery. B is a bar of iron suspended by threads. When a current passes in the coil the bar is magnetised and then sucked into the coil.

I have now to show you that if a rod of iron be placed inside this coil of wire carrying a current the magnetic field induces magnetisation in the iron. We will make the experiment. There is now no current in the wire coil and the iron bar does not attract these nails to it. I now connect the coil with a voltaic cell, the current flows and now the bar is magnetised. This discovery was made by Sturgeon.

Finally, I suspend the iron bar with only one end inside the coil. The current magnetises it, and then attracts its nearest end. So you see the iron bar is sucked into the coil so soon as a current passes (fig. 7).

This action of the coil and iron bar is called a *solenoidal* action by many people, and they call the combination of coil and iron a *solenoid*. I hope that none of you will ever use these terms so. It is quite inaccurate. I mention the words only so that you may understand them when you hear unpractical men use them. This sucking action is applicable to many pieces of apparatus. It is much used in the regulating part of arc lamps. It is usefully employed in this piece of apparatus, which is an electric hammer. Here is a vertical tube, wound continuously with a coil of wire from bottom to top. At every fifth turn there is a separate wire led away to one of these pieces of brass, of which there are fifty in line, along the base of the apparatus. The lowest five turns are connected at their beginning and end with the first and second pieces of brass, the next five with the second and third, and so on till we come to the last piece of brass, which is connected with the last turn of wire at the top of the column. Now I take this piece of wood, which can slide over the bits of brass. The wood has two metal contact pieces connected by wire with the copper and zinc of a battery. By rubbing the wood along I can pass the current of the battery through any section of coils in the vertical column that I please. I can begin by making a strong magnetic field at the bottom of the tube, and by sliding the contact I can raise the magnetic field gradually. If I now place a rod of iron in the tube, and move the slider backwards and forwards, I can raise and depress the iron core with great force. The apparatus is only a toy, but it illustrates well the sucking action of circular currents.

We have seen now a second logical deduction from Oersted's experiment—namely, that a current of electricity can convert soft iron into a magnet. When the current is in the form of a ring the action is most powerful, but this power exists wherever we have an electric current. You have seen when we were last together the position taken up by iron filings when placed in a magnetic field. I have here a horizontal glass plate with a hole in it. A vertical wire, carrying an electric current, passes through the hole. By means of the lime-light and two inclined mirrors, I can throw an image of the glass plate with its hole and wire on the wall. I now scatter iron filings on the glass and tap it. The filings get magnetised by the current, and set themselves along the lines in which magnetic induction acts. You see that these lines are circles surrounding the electric current (fig. 8).

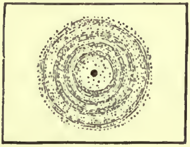

FIG. 8.—Circular magnetic field.

I have another way of showing the magnetic effect of the current. I dip this wire, carrying an electric current, into a box of iron filings. On lifting it out and placing it in the beam from the electric arc light you see its shadow on the screen with a thick cluster of filings adhering (fig. 9). The current magnetises each bit of iron. The ends of these bits attract each other, and form, as it were, flexible chains.

The end of the chain, which is a north pole, is urged round the current one way, the other end the other way, and so the wire carrying the current is gripped by the flexible mass of filings.

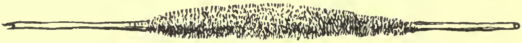

FIG. 9.—Wire carrying current after being dipped in iron filings.

I am now going to ask you to direct your attention to another conclusion which may be drawn from Oersted's experiment, and which leads us directly to one of Faraday's most beautiful discoveries. And I believe that in so thinking over Oersted's experiment, and leading up to the great discoveries of Faraday, we are following in the path which was trod by him. Faraday, in describing his work, never tells us that he knew beforehand what results he was going to get. He always described his experiments in order, and deduced his conclusions; but I do not think he could have been led to all the discoveries he made without foreseeing his results from theoretical considerations. It is perfectly well known that Newton obtained many of his results in dynamics by analytical methods before presenting them to the world in the geometrical form which best suited his age. It is equally true that many philosophers in our days have deduced their results geometrically before giving them the analytical garb which is most powerful in modern quantitative research. So do I conceive that Faraday applied the laws of motion and the then unwritten law of the conservation of energy to his science before ever touching wire or battery, and illustrated his results by experiments which were beyond cavil, and whose interpretation did not involve any physical intuition which was in advance of the science of the period.

We have found that the north pole of a magnet tends to move round a current in the direction indicated by our corkscrew aid to memory. Now we know that in all manifestations of force action and reaction are always equal and opposite. If I pull a weight on the floor towards me by a string the weight exerts on me a force exactly equal to that which I exert on the weight. If there were no friction on the floor the weight and myself would both slip along, and our relative motions would always be proportioned to our weights—the heavier of us moving least—the total action being equal to the total reaction. If the weight moved on wheels without friction, while I was fixed, the action on the weight would give rise to a reaction on myself, the floor and the whole globe, as one mass, in the opposite direction. When a stone falls to the ground the world jumps to the stone but the quantity of motion is proportional to the masses, so the world barely moves. The more you think over these examples the readier you will be to accept the universal law, which has never been violated in nature, that action and reaction are always equal and opposite. Now let us apply this to Oersted's experiment. We know that a magnetic pole tends to rotate round an electric current. We know that action and reaction are always equal and opposite. Therefore we know, with absolute certainty, before ever we try an experiment that an electric current tends to rotate round a magnetic pole in the same direction as that given by our corkscrew aid to memory. This is true, for you will easily see that if the reaction of a current is opposite to the action of the magnet they will rotate round each other and therefore rotate in the same way. To show this reaction Faraday devised the apparatus before you (fig. 10). It is the converse of one we previously used. It consists of a vertical magnet, with its south pole uppermost. Pivoted on the top of the magnet is one end of a conducting wire, which is bent down parallel to the magnet and dips into a ring-trough of mercury fixed to the middle of the magnet. I connect the magnet itself with the copper of a battery. The current passes through the magnet to the pivot at the top, which dips in a mercury cup, through the conducting wire downwards to the mercury trough and thence by a wire to the zinc of the battery. The circuit is now completed and the wire carrying the current moves round the south pole of the magnet in the opposite direction to the hands of a watch as we look down upon it. I have only to reverse the current to show you that the direction of rotation is changed.

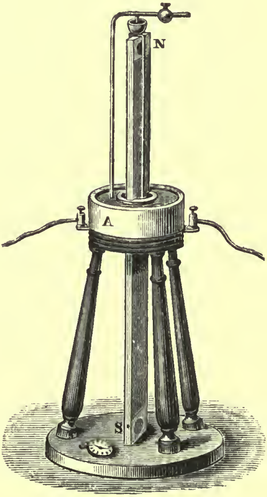

FIG. 10.

Current A rotates round north pole, N, with the hands of a watch.

Again I modify the experiment, by inverting the magnet having the north pole uppermost; and again you see the direction is reversed. Reversal of direction of current or inversion of magnetic poles reverses the direction of motion.

This result led Faraday to devise many beautiful experiments, all illustrating the same point; and the general fact remains established that when we have an electric current in a magnetic field—that is to say, in a part of space where there is magnetic induction, and cutting the direction of induction, then there is a force tending to move the magnet, and an equal force tending to move the current in the opposite direction; and whichever is free by the construction of the apparatus to move will move, and if both be free to move both will move. If, then, you place the right hand between the electric current and a north magnetic pole, with the fingers pointing in the direction of the current and the palm facing the north pole, then the thumb indicates the motion of the magnet,

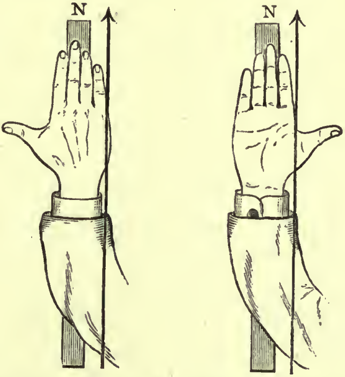

FIG. 11.—Diagram to illustrate rotative motion of magnet and current.

and if the palm face the current the thumb indicates the direction of the conductor carrying the current (fig. 11).

I will now illustrate the subject by means of a different apparatus, a piece of apparatus of great beauty, and one which with the same fidelity proves the truth of a current of electricity round a magnet. I have here a globe partially exhausted of air, the density of the air within it is very much less than the density of the atmosphere around us. I shall pass a current of electricity through this globe, passing it along the outside of the tube which goes down from the top through the middle of the globe.

Within that tube I have a piece of iron with a coil of wire round it, so that with the wires connected to a battery I am able to magnetise that central piece of iron either with the north pole downwards, or with the south pole downwards. We have seen that when a current is travelling parallel to a magnet it tends to rotate round it in one direction or another according to the direction of the magnetisation. In those experiments we always used a solid body, generally a copper wire, to convey the current of electricity. In this case I am going to pass the current of electricity through attenuated air. When we send a current by means of that grand induction coil through the partial vacuum, you see a stream of electricity; a current is passing parallel to the magnet from the top to the bottom. I am now able by means of a commutator to magnetise that bar of iron. I will magnetise it first with the north pole downwards, and you see a continuous rotation of the current of electricity round the pole of the magnet. I will now reverse the direction of magnetisation, and put the south pole downwards in place of the north pole; the current stops and immediately rotates in the opposite direction.

Now I must proceed to a fourth deduction from Oersted's experiment. When a coil of wire carrying an electric current is placed near a magnetic pole it attracts or repels that pole. If the pole is taken to the other side of the coil repulsion takes the place of attraction and *vice versâ*. We deduced all this directly from Oersted's experiment and confirmed our logic by experiment. The coil, then, with a current in it acts on external objects like a magnet. One of the open ends of the coil acts like a north pole and the other like a south pole. It follows that in the experiment I have just referred to we may replace the magnet by a coil carrying a current, and the action of these two current-carrying coils on each other must be the same as the action of two magnets on each other. Two circular coils facing each other, with a current going in the same direction in each, must act like two magnets end to end with their north poles pointing the same way, which as we know gives us attraction. Here we have arrived at a grand generalisation which is the section of electro-magnetism developed by the French philosopher Ampère. We will, as before, confirm our logic by the test of experience. I have here (fig. 12) two coils of wire suspended at the ends of a horizontal bar of wood. The axis of each coil is at right angles to the bar and horizontal. One end of each wire coil are connected together, the other loose ends go to the middle of the bar, and are attached to two fine vertical wires which form a suspension to the bar with great freedom of movement. The tops of the two wires are connected with the copper and zinc of a voltaic battery. The coils are so wound that the current flows in opposite directions in the two. This is done to overcome the effects of the earth's magnetism, which tends to twist each coil in the opposite direction. I hold in my hand two coils similarly mounted on a bar of wood and connected with another voltaic battery. The current here traverses both coils in the same direction. If I bring them in proximity

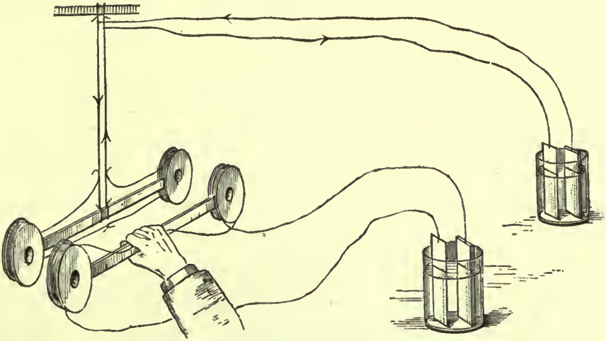

FIG. 12.—Ampère's experiment.

to the suspended pair, the direction of currents is such that one pair of opposing coils attract and the other pair repel. The result is rotation, as you now see, in the direction of the hands of a watch with its face upwards. I reverse the current in the coils I hold and the rotation is now in the opposite direction. Our fourth logical deduction from Oersted's experiment has stood the test of experience.

Having now grasped the fact that two circular currents face to face going the same way attract each other, let us for a moment divest our minds of the magnetic notions which have been our faithful guide so far, and look at the bare fact in another way as Ampère did. We are driven to the conclusion that two parallel bits of a current-carrying wire attract each other if the currents are going the same way, and repel if in opposite directions. I have here a piece of apparatus (fig. 13) consisting of a vertical column supporting at its top in a mercury cup a pivot attached to a horizontal wire, which after being bent downwards dips into a trough of mercury on the base of the apparatus. The mercury trough is connected with the zinc of a voltaic battery and the vertical column with the copper. The current then is flowing downwards in the wire. I hold in my hand a second wire connected with another battery. I have fixed a paper arrow on the wire to indicate the direction of the current. Pointing this arrow downwards the two currents are in the same direction. I bring my one near to the suspended one and you see there is attraction. It is now moving fast. I retain the downward motion of my current but put it to the other side of the suspended wire. The motion is checked by the attraction, and now the wire moves the opposite way. I invert my wire, the currents are now going in opposite directions. I approach the wire and repulsion takes place.

There is another part of Ampère's conclusions to which I will now direct your attention. Two magnets inclined to each other and left to themselves set their axes parallel, or in the same line. Hence, two coils must do the same, and will turn until they are parallel with the currents flowing in the same direction. It thus may be concluded, if we look at the action of one bit of current-carrying wire upon another, that if they are inclined at an acute angle, and if both of the neighbouring currents are going to the point of intersection, the acute angle will diminish; if one goes to, and the other from, the point of intersection the acute angle will expand.

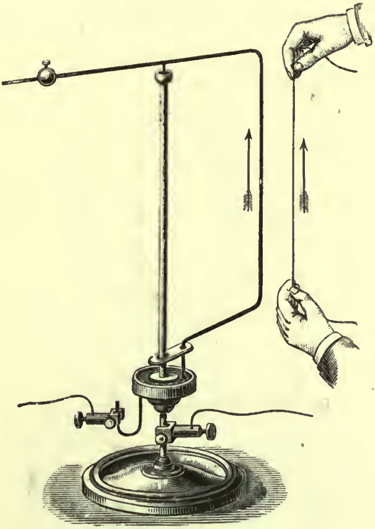

FIG. 13.—Mutual repulsion of parallel currents going in same direction.

The point is very nicely illustrated by this exceedingly beautiful though simple apparatus (fig. 14), which I happened to come across the other day. I dare say it is common enough, but I never saw it before. There are two coils of wire both upon vertical pivots, each capable of rotating on a vertical axis. A current of electricity can be independently sent through these two coils; both of them in rotating are able to make contact between the ends of the wire and two little mercury ring-troughs. The ends of the outer coil always dip into the same two troughs which are concentric. Hence the direction of the electric current in the outer coil is never changed. The ends of the other coil dip into a ring-trough with a partition, and the mercury rises by its surface tension above the level of the partition. Thus we have two mercury sectors into which the wires can dip, and this acts as a commutator, tending to reverse the direction of the electric current in the inner coil at each half-revolution. We can see that by this arrangement there is attraction up to a certain point. The momentum of the coil carries it past the dead point, and the current is now reversed, and repulsion takes place, continuing the rotation. By this ingenious device we get continuous rotation of both coils about a vertical axis in

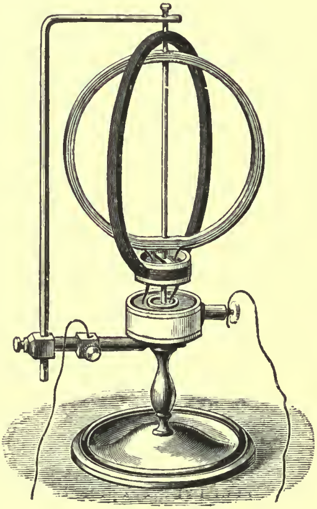

FIG. 14.

opposite directions. The very pretty contrivance illustrates the action I have been describing—namely, attraction or repulsion between parallel current conductors and a twisting force between them when crossed.

In conclusion of these illustrations I will now show you one which illustrates in a simple and effective manner the mutual attraction of parallel current-carrying conductors. I have upon this stand (fig. 15) a spiral of copper wire forming a vertical coil freely suspended from its top. The lower end dips into a vessel containing mercury, which is itself connected with one pole of a voltaic battery. The top of the spiral is connected to the other pole. When I turn on the current we know that there will be attraction between successive turns of the spiral. This being due, as we have seen, to the creation of a magnetic field by each turn of the spiral, the field would be strengthened by putting an iron rod inside the coil, and the attraction would

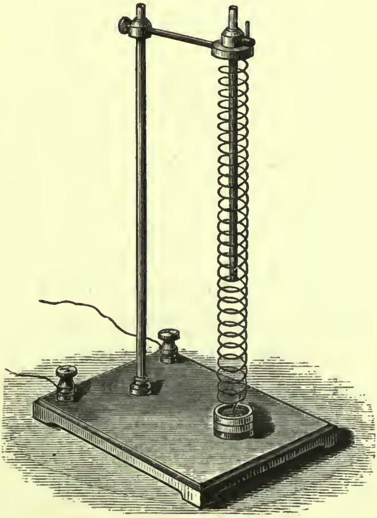

Fig. 15.

be greater. But you will see even without the iron that attraction will take place. The result of the attraction between neighbouring spirals is that the lower end of the wire is lifted quite out of the mercury. The current is then stopped, the spiral regains its natural length, re-establishing electric contact, renewing the attraction, and so again lifting the point out. Thus the point oscillates up and down many times a second, and each time the contact is broken a spark occurs with slight noise, and so you hear a continuous musical note from the intermittent action of the spiral's self-attraction.

In concluding this lecture I will remind you that from Oersted's experiment we have deduced and proved four conclusions: first, a magnetic pole tends to rotate continuously round an electric current; second, iron can be converted into a magnet by coiling a wire round it and passing an electric current through it; third, a current-carrying conductor tends to rotate round a magnetic pole; fourth, two wires carrying currents act upon each other like magnets. The directions of motions have also been clearly predicted and the predictions confirmed by trial. The connection between electric and magnetic action has been so clear that the idea of a magnetic molecule being a circular electric current commends itself to us. In any case, we may feel pretty sure that, if we know the physical cause of attraction and repulsion between two current-carrying conductors, we shall be not far from explaining the physical cause of magnetism. We learnt in the first lecture that the repulsion between two positively electrified bodies is due to a certain state of stress in the separating medium. To complete the foundations of a theory we must show why these stresses are so altered by a rapid parallel motion of the two electrified bodies, as to superadd to their natural repulsion an attraction which we know them to have, since it has been proved that an electric current is identical in its symptoms with a moving electrified body, and two parallel electric currents in the same direction attract each other.

Before we separate let me draw your attention to the boundless field laid open to the inventor by these discoveries of the philosophers. If we have a wire thousands of miles long, and returning parallel to itself, we can create a difference of potential between the two ends by means of an electric battery, and the current set up is capable of detection at the distant end almost instantaneously. Here is the key to the electric telegraph. The rapidity with which the signal can be detected depends upon the delicacy of the distant apparatus, or the means used for detecting the presence of a current in the wire. Cooke and Wheatstone passed the electric current at the distant end through a galvanometer. Morse used an electromagnet which attracted a piece of iron each time a current passed. Bain used a solution of iodide of potassium and starch on a strip of paper. The solution was decomposed, and left a blue mark on the paper when a current was passing. The construction of an alphabet from these signals was not difficult. Cooke and Wheatstone sent the current in one or other direction to give two kinds of signals, the combinations of two, three, or four of these signals gave all the letters of the alphabet. Morse used currents of short and long duration for his two primary signals, the dot and the dash, and combined them in the same way. Hughes caused a wheel with types on its edge to revolve continuously over a sheet of paper, and when the required letter was in place a current going through an electromagnet caused it to make a mark on the paper. This involved accurate synchronism between moving apparatus at the sending and receiving end. Numbers of telegraphs have been invented which depend upon synchronism.

A great advance in telegraphy was made when it was found that a return wire was unnecessary. At the distant end the wire is connected with the ground. At the sending end it is connected with one pole of the battery, the other pole being connected to the ground. The whole world is used as the return conductor.

Clocks can be regulated at any distance by an electric current. A central controlling clock may make connection at every swing of the pendulum between one pole of a battery and a wire. This wire may go to all the clocks in a district, and at each second the current acts by one or other of the electromagnetic actions we have examined so as to accelerate or retard them as required. In another system a signal is sent to all the clocks once an hour, and the current is used to pinch the minute hand and set it exactly to XII.

The construction of bells on electromagnetic principles is not difficult to the inventor. Almost any kind of recording or tell-tale apparatus for water levels, height of barometer or thermometer, for recording the hour when a watchman makes each visit, can be invented with no great exercise of ingenuity. The commercial and industrial applications following from Oersted's great discovery are innumerable.

LECTURE V.

ELECTROMAGNETIC INDUCTION.

In the last lecture we studied the remarkable experiment of Oersted. This experiment bears the same relation to the laws of electricity as Kepler's calculations bore to the laws of gravitation. Each is a bare statement of fact, but in each is contained the germ of the whole truth, which only required to be put into mathematical language to complete the theory. Newton did this for gravitation, Ampère did the same for electromagnetism. It has been said by some that it was by an accident that Oersted made his discovery. If that be the definition of accidental discovery I should be inclined to say that it was by accident that Kepler found out that the planets revolve in ellipses with the sun in the foci; it was by an accident that Herschel discovered the planet Uranus; the minor planets were found by accident, and nearly all geographical discoveries have been accidental; the discovery of the variation of heat-conductivity in iron with temperature was accidental, and most laboratory discoveries are accidental. It is true that when Oersted made his brilliant discovery he was trying to obtain some effect on the compass needle by the heat developed in a wire by the electric current. But what would be the value of laboratory research if we never discovered anything except what we expected? The only men who can make these accidental discoveries are the men who are continually experimenting with laborious industry, and who have the tenacity of purpose required for tracking every unknown effect to its cause, and whose experience enables them to realise the importance of an unexpected result. There are too few of these original workers at present. We want some more men, who know how to hunt for such accidental discoveries. Of late years the pursuit of physical science has become a profession followed for the purpose of making an income. The investigator of to-day sets before himself a research in which he knows beforehand the qualitative results he will obtain. He becomes little more than a measuring machine. He completes his research without meeting with a single unexpected result. He publishes his research in a scientific society's transactions with his results carefully tabulated and illustrated by curves. Such men do good, useful work. The care and skill required for such researches is great and requires a long period of training, and the work has a money value which can be reckoned at so much an hour. But no amount of income paid will create the original discoverer who makes discoveries by accident. His accidental discoveries are not to be valued by a standard of money or by time spent on them. It is genius that leads to these accidents—the genius of a Kepler, of an Oersted, of a Faraday.

We have seen that Oersted's discovery leads directly to the continuous rotation of a magnetic pole round a current, to the making of electromagnets, to the rotation of a current round a magnetic pole, and to the mutual action of two electric currents. But this in no way detracts from the value and originality of the work of Faraday, Ampère, and Sturgeon, who added new facts to science. And so it is in the present day. We frequently meet with new discoveries which, upon investigation, are found to be deducible from what we knew before; but this does not in any way diminish the merit of those discoverers who have added to our knowledge of facts. And this is especially so in the realm of electricity.

I have the intention to-day of dealing with a fifth conclusion which might be drawn from Oersted's experiment, and which has led to as many useful applications as any of the facts established in our last lecture.

Let us apply to Oersted's experiment the principle of the conservation of energy which has been developed in the last half-century. Lucretius told us, 'Ex nihilo nihil fit' ('Nothing comes from nothing'). He meant this to apply to matter, and his maxim is the fundamental basis of the analytical chemist's art. 'The quantity of matter in the universe never changes;' that is how he expresses the maxim of Lucretius. But the physical philosopher has extended the meaning of that maxim. He applies it to energy as well as to matter, and declares that the total quantity of energy in the universe never changes. We may transform the energy of a moving body into energy of heat. The energies of electrical action and chemical affinity can be interchanged, but we can never alter the quantity of energy though we may change its form.

Now apply this to Oersted's experiment. A compass needle is held in the meridian by the force of the earth's magnetism. An electric current is caused to flow parallel to it. The needle moves through a certain angle against the directive force of the earth's magnetism. During this action a certain amount of work is done. Energy must have been expended in doing this work and giving to the compass needle an energy of position with respect to the direction of the earth's magnetism. Whence has this energy been derived? Some part of the apparatus must have lost an equal amount of energy. The only source of energy in the apparatus is the electric current, and we may be absolutely certain that when the compass needle moved the electric current in the wire was diminished. Now the electric current in a conducting circuit depends upon the electromotive force acting in that circuit and on the resistance of the circuit. The latter quantity cannot change, and now we know that the electromotive force in the circuit has been diminished during the motion of the compass needle. The motion of the needle has caused the production of a momentary counter-electromotive force opposed to that of the battery.

Let us make our ideas clearer by considering a special case. An electric current flows in a wire from north to south over a compass needle, which moves through a definite angle, the north end going to the east, doing a measurable amount of work against the force of the earth's magnetism. This is accompanied, as we have now assured ourselves, by the creation of an electromotive force tending to set up an electric current in the wire from south to north. We have learnt, then, from Oersted's experiment and the conservation of energy, that if part of a conducting circuit be over a compass needle and the needle be deflected, its north end being moved to the east, a current is induced in the circuit from south to north.

Precisely the same reasoning applies to all the cases where in the last lecture we obtained motion by electromagnetic action, for work is always done in these cases by motion against friction if not against the earth's magnetism. See what a field for experimental verification lies before us! We may well be appalled by the importance of this last logical deduction from Oersted's experiment. We are now in a position to assert that when a magnetic pole is caused to rotate round part of a conducting circuit a current is induced in that circuit. The same happens if part of the circuit rotates round the magnetic pole. Further, we can state that if the north pole of a magnet enters a coil of wire a current in one direction is started in the wire. If the north pole be withdrawn a reverse current is induced. Another current in this reverse direction is induced by the introduction of a south magnetic pole, the withdrawal of which induces a current agreeing in direction with the first in this series. We can still further affirm that if two coils of wire lie face to face, and a current of electricity is in one of them, then the approach of the two coils together creates a reverse current in the second one; the separation of the coils induces one agreeing in direction with itself.

Now let us put these most important assertions to the test of experiment. In order to detect the existence of induced currents I will make use of this reflecting galvanometer on the mantelpiece. It consists of a small magnet attached to a mirror and placed inside a coil of wire. The magnet points north and south. The axis of the coil lies east and west. To the ends of the coil of wire I can attach the ends of any other wire in which I wish to detect the existence of an induced electromotive force. The lime-light in this lantern shining on the mirror throws a spot of light on the wall, and the moving vertical line you see is the reflected image of a wire in the lantern. Its motion to right or left indicates the existence and direction of an electric current in the coil of the galvanometer. You will understand in the experiments we are engaged on the relative motions of wires and magnet may induce an electromotive force without necessarily inducing a current, if the wire circuit be not closed. I do not say it is so but it may be. Certainly in all the cases I have suggested an electromotive force is induced whether the circuit is open or closed.

I will commence by connecting the ends of the galvanometer-wire to the ends of another wire coil which I shall use at some distance away. I now hold the coil in one hand, a magnet in the other. I will force the north pole of the magnet into the coil towards you (fig. 1). On doing so you see the spot of light moves to the right. If our theory be true it must be found that on withdrawing the magnet a reverse current is induced. You see the spot of light moves to the left. I reverse my hold of the magnet, and introduce the south pole towards you. The spot of light moves to the left again. I complete the experiment by withdrawing the south pole, and we get a motion in the original direction—namely, to the right.

One of the most beautiful applications of Faraday's discovery, that an electric current is created in a wire when a magnet moves in its neighbourhood, is found in the magneto-telephone of Mr. A. Graham Bell, by means of which speech in one place can be reproduced in another place connected ~~with it by an electric~~ conductor such as a telegraph wire. Speech consists of a series of vibrations of the air, which vibrations strike the ear, and also strike all

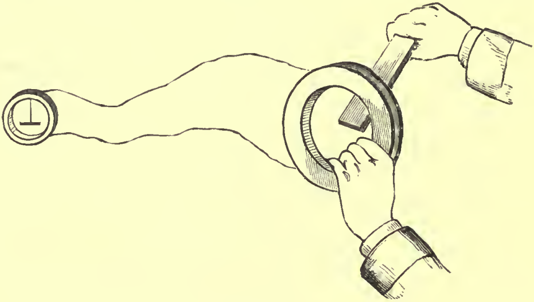

FIG. 1.

objects within range of the speaker. It occurred to Bell to allow a thin sheet of iron to be acted on by the air vibrations so that it should itself vibrate. A coil of insulated wire was placed facing the iron sheet. The iron was magnetised by a magnet whose pole almost touched it, and which passed through the coil of insulated wire. Bell said that if the magnetised iron sheet moves in accordance with the vibration of the air due to speech, then electric currents will be created in the coil of wire, and these currents can be transmitted to a distance by a telegraph wire. The frequency of the air vibrations, and their intensity will be reproduced by the frequency and intensity of the electric currents. If now a similar instrument be placed at the distant place, its wire coil being also connected with the telegraph wire, the electric currents passing through the coil will attract and repel the thin iron sheet which will give off to the air vibrations exactly resembling in frequency and relative magnitude the vibrations caused by the original speaker, and these air vibrations can be listened to by putting the ear close to the second instrument.

I will now show you the action of a piece of apparatus which I have mounted here (fig. 3) to illustrate this principle of the telephone.

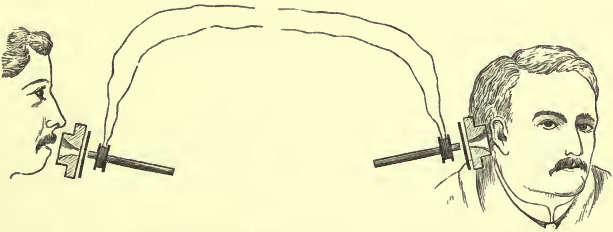

Fig. 2.—Illustration of the action of a pair of telephones.

I have suspended a sheet of iron in front of the pole of a magnet. The magnet is placed inside a coil of wire. The two ends of the wire coil pass away to this second apparatus, namely, a coil of wire round a magnet. Here I hold a mass of iron in front of the magnet pole, and move it by hand backwards and forwards. I time the movements so as to sympathise with the oscillations of the suspended iron sheet. The electric light now throws a shadow of the suspended iron sheet on the screen, and you can see it oscillating in sympathy with the movement ot the iron mass I hold.

The discovery of electric currents created or induced by electromagnetic action fell to the lot of Faraday. He did not rest content with a single experiment. He was not content with being the first to convert the muscular energy required for approaching a coil and a magnet into electrical energy. He saw most clearly that his discovery of induction opened out a new mine of electric energy, which could now be obtained without limit from any source of mechanical power, such as a waterfall or steam engine. But he knew well enough that while there would be plenty of workers to magnify the scale of his experiments when the money reward of a useful invention was in view, there were comparatively few who had the knack, let us call it, of attaining new qualitative results.

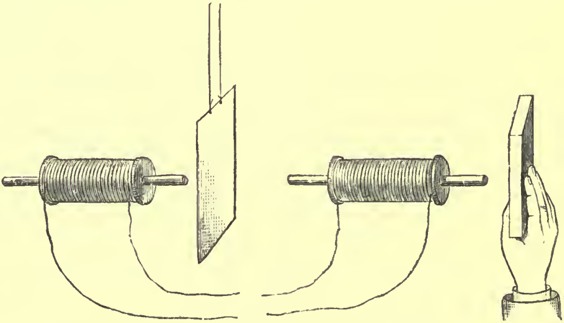

FIG. 3.—Illustration of the action of telephones.

He went on step by step adding to the sum of human knowledge, and evolved the whole science of induced currents. Long afterwards, when Holmes had worked out these principles and made a machine, driven by steam, for generating an electric current for producing the electric light in lighthouses, Faraday looked at the machine and said, 'I gave you a baby and you bring me a giant.'

The same line of argument which led us to expect an electromotive force to be induced by the relative motion of a coil of wire and a magnet leads us to other methods of inducing an electromotive force in a wire. Ampère had found that when two coils of wire were placed in proximity to each other, and currents of electricity were flowing through both in the same direction there was an attraction between them. Exactly similar reasoning to that previously employed leads us to the conclusion that, while the currents are approaching, each induces a counter electromotive force in the other. If only one of the coils have an electric current then its approach will cause an electromotive force to ~~be induced in the~~ other, tending to set up a current opposed in direction to that of the primary coil. So also the withdrawal of the primary coil carrying an electric current induces an electromotive force in the second coil, tending to make an electric current in the same direction as that of the primary coil. Here I have two coils of insulated wire (fig. 4). One of them has its ends connected to the ends of the wire coil of the mirror-galvanometer. The other one has its ends connected to the zinc and copper of a voltaic battery. The spot of light on the screen, reflected from the mirror of the galvanometer, is now quite steady. I now cause one coil to approach the other. The presence of an inverse current is now shown by a violent motion of the spot of light to the left. I withdraw one of the coils and the spot moves to the right, showing a current in the opposite direction.

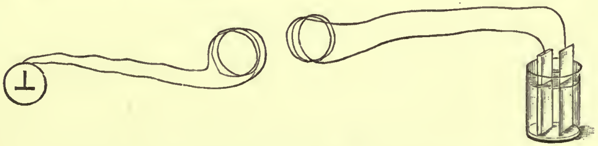

FIG. 4.—Experiment showing induced currents.

From the experiment which has just been done it is an easy step to the next experiment. The action which has taken place is the same as when a magnet pole was brought near to a wire coil. A wire coil, carrying an electric current magnetises the surrounding space just as a magnet does, and a current was induced in the secondary coil by approach of the primary only because this action intensified the magnetic field inside the secondary coil. The same result will be attained if I fix the two coils in position and suddenly start a current in one of them. Now I complete the electric circuit with the battery and primary coil. An inverse electromotive force is induced in the secondary coil, starting a momentary current in the coils of the galvanometer, as shown by the motion of the reflected spot of light to the left. The action has now ceased. The spot of light is in its position of rest. I break the primary circuit and the spot of light moves to the right.

I will further amplify the experiment by showing you the enormous influence of the introduction of a bar of iron passing through both coils. The intensification of the magnetic field inside the secondary coil when I make contact will now be very much greater. See now with what a sudden jerk the light spot moves, and how it flies half round the room. You will please bear well in mind the fact which you have noticed in all these experiments that the action of induction is taking place only during the increase or decrease of the strength of the magnetic field. After I have ceased moving the coils no further current is induced. When the current in the primary is being made or broken the induction takes place only during the infinitesimal portion of time required to start or stop the current. You will also remember that a current is induced in a conducting circuit only while the intensity of the magnetic field within that circuit is in the act of increasing or diminishing. This fact has been put in another form by saying that a current is induced in a conducting circuit while the number of magnetic lines of induction (lines of force as Faraday called them) is increasing or diminishing. You may also be assisted in understanding many experiments if you remember that an electromotive force may be induced in a conductor which is moving across a magnetic field even though the conducting circuit be not completed so as to allow of any current passing.

These inestimably valuable discoveries of Faraday were not completed in a day. It is all very well for us just to look at a few conclusive experiments as these, and to say that they are the necessary deductions from Oersted's experiments. But the philosopher who is discovering new facts is by no means so readily satisfied, and it took some of the best years of Faraday's life to establish the truth of the laws of induction. He tested his conclusions by new inferences which might be proved by experiment. As an example he showed that terrestrial magnetism was sufficient to induce a current of electricity in a moving wire, as I will show you by means of this piece of apparatus (Fig. 5), to which I beg you to give your most serious attention. Here is a rectangular coil of wire to which I can give rotation about a horizontal axis so that it can cut the magnetic field created by the earth's magnetism, the earth's magnetic action being pretty nearly vertical—20° from the vertical—in this latitude. You see that at any moment while the upper half of the coil is cutting the lines of induction in one direction, the lower half is cutting them in the other direction. It follows that an electric current is created from your left to your right in one half of the coil, and in the opposite direction in the other side of the coil. The combined effect of this is to produce in both parts a continuous current round the coil in one direction. But after this has been going on for half a revolution you can see that in the next half-revolution the current in the wires will be reversed. To cause the direction of the current which we had to the galvanometer to be always the same the two ends of the wire coil are not always connected to the same wires going to the galvanometer. A rubbing connection is made between the wires going to the galvanometer and the ends of the revolving wire coil, so that the upper wire going to the galvanometer is always in contact with the end of wire coming from the upper part of the coil, and the lower wire going to the galvanometer is always in contact with the ends of wire coming from the lower part of the coil. This rubbing contact, changing the electrical connections at each half-revolution of the coil, is called a commutator, and you can see that by its action the current in the galvanometer will be continuous in direction. I rotate the coil with a rotation in one direction, and you see we have a sustained deflection of the spot of light to the left. I reverse the direction of rotation and the light moves to the right. Here the deflection of the galvanometer needle is maintained so long as the coils rotate. The commutator enables us to accumulate the successive temporary currents of the rotating coil.

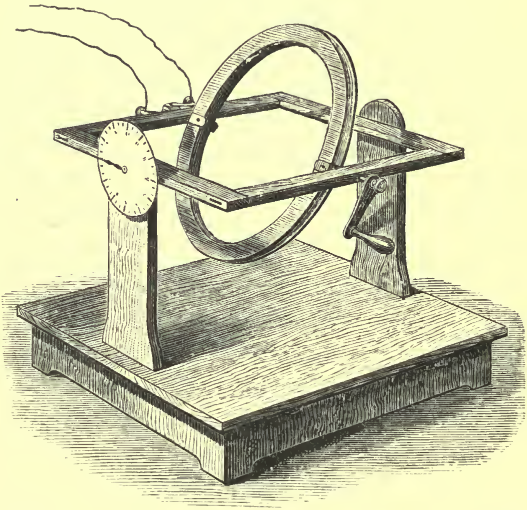

FIG. 5.—Experiment showing currents induced by terrestrial magnetism.

I trust that you have been able thoroughly to understand the action of the apparatus, because it is a type of those powerful dynamo machines which we now use for producing the electric light and for electroplating. The essential parts are—a rotating coil, a magnetic field where the lines of induction cut the coil, and a commutator. If I put the coil between the poles of a powerful magnet I have a much more intense field than what the earth produces. If I fill up the empty space in the middle of the coil with iron I still further intensify the magnetic field cut by the revolving coil. Here is the revolving part of one of the old Siemens and Halske dynamo machines, and here is the fixed magnet which creates the magnetic field (fig. 6). The revolving part is called an *armature*. You see it consists of wire wound on an iron shuttle. The ends of wire are attached to two halves of a split tube, which form the commutator. Springs are fixed so as to rub on these, and the springs (or brushes as they are often called) form the terminals of the machine to which can be attached the wire ends of any conducting circuit through which we wish to pass an electric current. In the Siemens and Halske machines the magnetic field was produced by permanent steel magnets. In modern machines the more powerful field produced by electromagnets is used. Such machines used to be named magneto- or dynamo-electric machines according as permanent magnets or electromagnets were used to produce the field. The general term dynamo machine—from the Greek δύναμις, power—is now given to all such

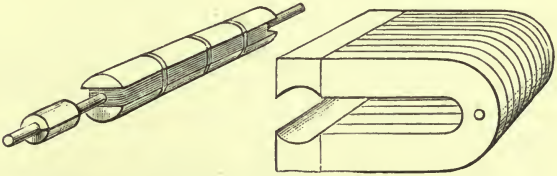

FIG. 6.—Siemens and Halske dynamo machine.

machines in which mechanical power is converted into electricity. Nearly all modern dynamo machines consist—(1) of electromagnets to give a strong magnetic field; (2) of revolving coils on an iron core forming the armature; and (3) of a commutator with brushes to render the current in the external circuit continuous in direction. When you look at a dynamo machine it will be a good exercise to identify the field magnets, the armature, the commutator, and the brushes. The field magnets and brushes are at rest, the armature and commutator revolve.

The most important modification introduced into many modern dynamos is in the winding of the armature and the subdividing of the commutator into a large number of parts. But were I to proceed to such details I should be converting this lecture into a purely technical lesson, whereas my object is rather to lay principles before you. What has been said will perhaps assist some of you in understanding special books upon the construction of dynamos.

The momentary currents of induction which can be produced by increasing or diminishing the strength of the magnetic field inside a coil are generally of great intensity during the short period of time that they last. I have upon the table an apparatus which illustrates one of these uses. It consists of a horse-shoe magnet of steel, with soft iron pole-pieces, and bobbins of wire are wound on to them. An iron keeper connects these poles and serves to direct a powerful magnetic field through the bobbins so long as it remains in place. A sudden removal of the iron keeper creates a powerful electromotive force in the bobbins which may be utilised for signalling and for other purposes. At present I have connected it by wires with some Abel's fuses for exploding mines. I jerk off the iron keeper and you see the fuses are fired.

I will now show you a few experiments with this magnificent induction coil by Apps (fig. 7), in order to realise what a high electromotive force can be obtained from a small voltaic battery by means of induction. The instrument consists of a thick bundle of iron wires round which many turns of a stout insulated copper wire are wound so as to form a primary coil through which the current from four voltaic cells can be passed. A secondary coil of very fine copper wire, most carefully insulated in sections, is wound over the primary. The two ends of this coil are attached to these knobs on the top of the instrument. In the primary circuit an automatic current interruptor is placed so that the current in the primary coil is made and broken in rapid succession, thus creating and destroying the magnetic intensity in the iron which penetrates both coils. Thus an electromotive force is generated in each turn of the secondary coil in one direction or the other, according as the primary current is made or broken. The fineness of wire on the secondary coil enables us to have an enormous number of turns, in each of which the electromotive force is generated. The sum total of these is such a great electromotive force that it approaches the effect produced by the Wimshurst machine which was at work in our first lecture. I place the terminals of the secondary coil six inches apart, and you see the sparks flying across when the

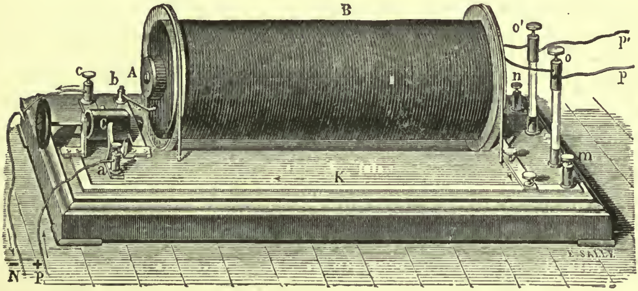

FIG. 7.—Rhumkorff coil.

interruptor is at work. By connecting the two terminals of the secondary coil with the inside and outside of the Leyden jar we get a shorter spark of greater body very suitable for spectroscopic examination. Here I have a slab of glass, half an inch thick, pierced by the spark from this coil.

I have on the table a similar apparatus without the interruptor constructed by Messrs. Gaulard and Gibbs for that marvellous means of distributing the electric current which they have invented. They call the apparatus a secondary generator. The first peculiarity of it is that the secondary coil is of low resistance. A current alternating in direction is sent through the primaries of a large number of these secondary generators in different houses, and the secondary coils are used to supply current to the electric lamps in the house. This current is of low electromotive force, because of the low resistance of the secondary coils, and is quite harmless, though the primary current may be actuated by a high electromotive force dangerous to life. This enables them to use thin telegraph wires to distribute the current to distances, at a moderate cost, while the secondary circuit, which alone is accessible, is quite safe. The astonishing part of the invention was that by a special arrangement they succeeded in obtaining out of the secondary coil almost as much electrical energy as was used in the primary coil, which was the first evidence that philosophers had of the small amount of energy used up in alternately magnetising iron in opposite directions.

There are many other experiments illustrating the important subject of induction which I should like to show you. Here I have a horizontal circular copper disc supported on a vertical axis to which I can give a rapid rotation. Above it is a sheet of glass, on which is a steel pivot for a large compass needle to rest on (Fig. 8). I rotate the copper disc, and you see that the compass needle rotates also in the same direction, though the glass plate prevents air-currents from reaching it. This was discovered by Arago, and Faraday showed it to be a consequence of those induced currents which he had been investigating. The explanation is simple, and beautiful in its simplicity. Pay attention to one pole of the compass needle; the copper conductor is moving through its magnetic field. Therefore a current is set up at that spot along a radius of the copper disc. This current in turn deflects the magnetic pole at right angles to a radius, and if you apply the laws of direction which we learnt from Oersted's experiment, you will find that the pole tends to move in the same direction as the copper disc, and that the same thing is happening with the other pole. Hence the compass needle rotates with the copper disc, though separated from all contact with it. This has always seemed to me to impress one with the idea of some medium between the disc and magnet communicating the motion.

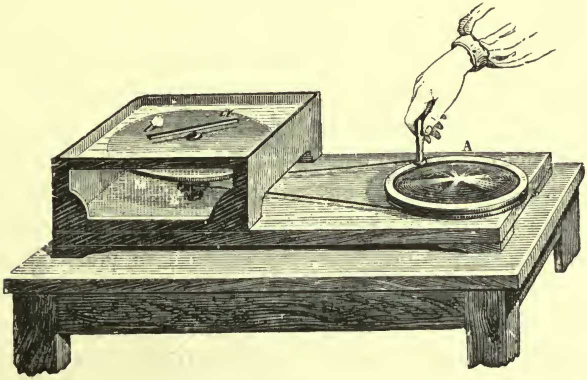

FIG. 8.—Arago's disc.

The phenomenon of Arago's disc, after it had been explained by Faraday, was studied by others, and further facts became known. I will show you one modification, which was first shown to me by Professor Guthrie,[1] and it seemed to me very striking indeed. I suspend from one end of a balance a horse-shoe magnet, with the poles just over the rotating copper disc. The magnet is exactly balanced by weights. I rotate the disc, and the magnet is repelled, and seems to be lighter. Whence this repulsion? If the current induced radially in the disc is directly underneath the pole of the needle its influence on the needle must be purely horizontal. If the induced current were carried round with the disc, so that it was in advance of the position occupied by the magnet pole, then there would be a vertical component, for the magnet pole is always moved perpendicularly to a line drawn from it to the electric current. This vertical component shows itself as a repulsion. It appears then that in a moving conductor the current is carried with the conductor. It looks as if a current once started tends to maintain itself. This is the correct view. The phenomenon is sometimes spoken of as electrokinetic momentum, from the analogy of the motion of matter which, when once started, tends to maintain its motion. This is a phenomenon which we constantly meet with in experiments on induction and in its practical applications.

I have said that Arago's disc always impresses me with the notion of a medium for transmitting the electric forces. Here is an experiment which does so perhaps even more strongly (fig. 9). I have here a copper medal, suspended, by a thread between the poles of a powerful electro-magnet which is not yet connected to the battery; and which is consequently non-magnetised. I give a twist to the thread, and set the medal spinning. It has now acquired considerable velocity. I convert the iron into a magnet.

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[1] He has left us since these words were spoken. Everyone who really knew him now mourns his loss. Nov. 6, 1886.

The medal stops spinning instantly. The quickly moving copper in the strong magnetic field has electric currents induced in it which are so acted upon by the magnet as to oppose the motion. This is a direct result of the mutual action of magnets and currents which we have studied, but it is a suggestive experiment.

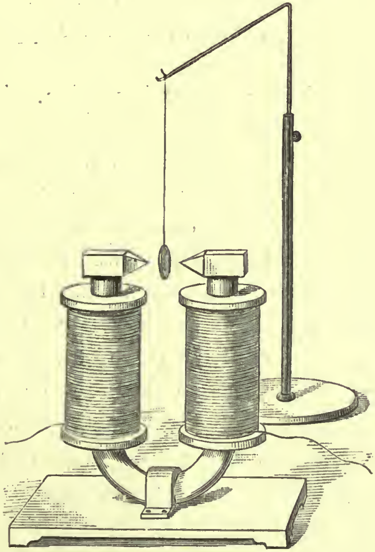

FIG. 9.

Were I to say all I should like to say about induction I fear I should be drawn into a technical tone, which would hardly be consistent with the character of these lectures. It has been our endeavour to survey some of the leading facts which form the foundations of our most absorbing science. Only one man has ever ventured to sketch a hypothesis to give a logical idea of mechanical actions which could explain the phenomena of electrokinetics. That man was James Clerk Maxwell. But even he in his great work on Electricity and Magnetism thought it wiser to leave hypothesis on one side and content himself with collecting the facts and views of Faraday into a complete and unassailable quantitative mathematical theory. I well remember, in 1874, when that great work appeared Professor Tait said to me: 'I must now make Thomson (Sir William) fulfil his promise. Twenty years ago he said to me, "Tell me what electricity is, and I will tell you everything else." Since Maxwell's book has appeared he must redeem his word.'

I have not said much about invention. The inventors of telegraphs, telephones, dynamo machines, and electric lights have applied the principles which we have been studying. This is a field for separate study. We have wandered over the field of electric discovery in a cursory manner, and, if I may so express it, we have had the modern conveniences of travel. We have not had to face the almost impassible mountain chain. We have passed from one place of interest to another without any delay on the road. When barren steppes have had to be crossed, our easy and rapid means of travel has landed us on the oasis to revel in its beauties. We have gloried in the achievements of the pioneers, but we have not known the toil they underwent and the long barren search before the discovery of each gem. We have learnt to revere the name of such a man as Faraday, not because he was the first to do this or to see that, but because through his long and toilsome life he had one pleasure—to learn more and more and to love the works of Nature and the laws by which she works, which become simpler and simpler the more they are known. Even among the utilitarianism of the present time such lives are still being lived. Long may the spirit of Faraday animate those whose privilege it is to add to the sum of human knowledge!

LECTURE VI.

DYNAMO-ELECTRIC MACHINERY.[1]

[Delivered at the International Electrical Exhibition of the Franklin Institute, Tuesday, September 16, 1884.]

THE subject of this evening's lecture is Dynamo-Electric Machinery, and it ought, perhaps, in greater strictness to be defined as dynamo-electric machinery in general, and not dynamo-electric machinery in detail; because in a single lecture it is impossible to go into the whole subject of the differences between various types of machines, and all I can hope to do in the course of this lecture is to give to you a general insight into the theory and principles of construction of dynamo machinery and of the progress which has been made up to the present time in theoretical investigation and practical application.

At the beginning of this century our information about the action of electrical currents was extremely limited indeed, and it was not until a great discovery was made in the year 1819 that the basis was laid for those developments which have culminated in the vast number of machines which you see around you in this Exhibition. At the commencement of the century, in fact up to quite a recent date, the current of electricity was developed, not by means of these machines which we see around us in the Exhibition, but by means of a chemical apparatus which was called a voltaic battery, such a one as I hold in my hand here, which consists of two dissimilar metals, one of which is zinc and the other may be of carbon, copper, or some other metal. When these two metals are dipped into a suitable acid and connected by a wire, a current of electricity is said to pass from the copper through that wire to the zinc. Now, if you ask me what is the current of electricity, I am bound to confess to you that I do not know. All that I can do is to give you some analogy to fix your mind upon while you are thinking about a current of electricity. If I were to take a copper wire and hold one end of it in a hot flame and hold the other end in a block of ice, heat would be absorbed in the end which was in the flame and heat would be given out in the end which was in the ice, and heat would be conducted along the wire. No material substance is conducted along that wire, and I am sure there are very few of you that can form any conception of what is passing on in the wire. But you have a notion, not a physical conception, of heat, and the phenomenon of heat transference through the wire is not unfamiliar to you. I do not say that electricity is the same as this, but it is the general opinion of scientific men that electricity passes through the wire in a somewhat similar manner to heat. It is probably energy and not matter which passes through the wire. That, however, is not a tangible analogy.

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[1] I have thought it desirable to add this lecture to the present volume. It goes over much of the ground in previous lectures, but it serves to connect the purely scientific work with one of the most important applications.—G. F.

I will try now to give you a clearer but grosser analogy. I allude to the analogy which exists between electricity and the flow of water in pipes. When we have a certain head or pressure of water we have also a flow of water through the pipes, and the greater the head or pressure the greater is the flow of water through the pipes. At the same time we have in the pipes a certain resistance to this flow, a resistance due to the small diameter of the pipe, and the smaller the diameter the greater the resistance to the flow of water. In all these points electricity has an analogue. We are able to get up what we call an electric pressure or electromotive force which exactly corresponds to the pressure of the head of water. When we have this electromotive force in the wire, we are able to get a current of electricity through the wire. That is to say, a flow of electricity which is exactly analogous to the flow of water in the pipes. But this wire offers a resistance to the passage of electricity just as the pipe offered a resistance to the flow of water, and the larger the wire is, and the greater its sectional area, the greater is the flow of electricity, just as the greater the diameter of the pipe, the greater is the flow of water. Thus, I think you will admit that we have here a tangible analogy between the flow of water and the flow of electricity; and when I speak of the electromotive force which we have, you will understand that it is analogous to the pressure of water, and when I speak of the resistance it is analogous to the frictional resistance to the flow of water in the pipe.

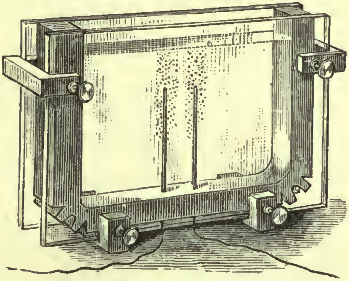

FIG. 1.—Decomposition of water by an electric current. (Cell upright.)

Previous to the year 1819 the important facts which were known in connection with the electric currents were these: First, that if two wires coming from a voltaic battery were dipped into a solution of acidulated water, the elements of which the water is composed were separated or decomposed and rose as bubbles to the surface. This experiment I can show to you now on the screen by means of the lantern. We will lower the lights. We have now a cell which is exhibited on an enormous scale on this screen in an inverted position. (See fig. 1.) Here is the top, and this is all air below; the cell being inverted the water which is contained in the cell is shown at the top of the picture; and here we have two wires; one is to be connected with the positive pole of the voltaic battery and the other with the negative pole. If now the wires be connected we shall see bubbles of gas, hydrogen and oxygen, rising to the surface. This shows a decomposition of the water in the cell in a manner such as it would be impossible for me to show to you on the lecture table.

Another fact which was known at the same time and which was one of the few important facts known was this: that if a conductor, made thin enough, were brought in connection with the two poles of the battery it would become red hot or white hot.

I have underneath this table a voltaic battery connected with two wires coming above the table. You will be able to see as soon as I connect them with a thin piece of platinum wire that the wire becomes red hot, and if I diminish the resistance in the circuit by shortening the wire I can make it even hotter than that; I am able to make this wire of a bright red heat.

These two important facts were then known—the decomposition of water, and the heating of a conductor, by the passage of an electric current. There was another fact that was known which I ought not to omit to mention: the discovery of Sir Humphry Davy, about the year 1811, that the spark which had often been seen on the breaking of the circuit could be intensified by using a large number of cells in a voltaic battery, and taking the two ends of the wire and attaching to them two pieces of charcoal, on separating these two pieces of charcoal a brilliant light was seen to pass from one piece of the charcoal to the other. That is the fundamental experiment which led to the discovery of the electric light, that is the arc light, which is so very much used in this country.

The next step made was, I believe, the most prolific experimental discovery ever made in science. It was made by Professor Oersted, of Copenhagen, on a compass needle. His discovery was the commencement and the dawn of the whole of that science of electricity which has reached such a culmination in this Exhibition, and the genesis of every one of the telegraph instruments in the Exhibition, of every one of those telephones, of all the various applications of electricity, of every one of the types of dynamos in this building.

For many years people were aware that there was some hidden connection between the compass and electricity, between the power that impelled the compass to point to the north and the lightning in the sky. It had been believed that when lightning had disarranged the compass needle and reversed its polarity it showed that there was some connection between electricity and magnetism, but no one could tell what that connection was. Mathematics were of no avail in the solution of this problem. Oersted happened to be experimenting with a battery and a compass, and found the secret of the mystery, and it is from this point that we have to investigate the progress of electricity this evening.

Here we have a compass needle suspended under a wire. (See fig. 2.) The wire will presently have an electric current passing through it. Oersted found that when the current coming from the copper pole passed over a compass needle from the south to the north, the compass needle moved with its north pole towards the west. That is, the compass needle was moved by the influence of the electric current, an action taking place between the

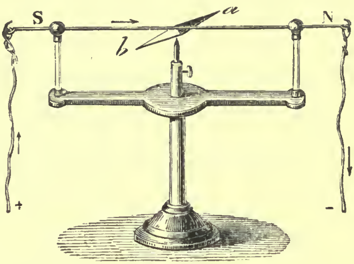

FIG. 2.—Action of an electric current on a compass needle.

current over it and itself. On this compass needle I have put some pieces of paper that you may be better able to see the experiment. If Mr. Knapp, who is kindly giving me his assistance, will now lower the plates into the battery you will immediately see a declination of the north pole of the compass to the west. On breaking the current the

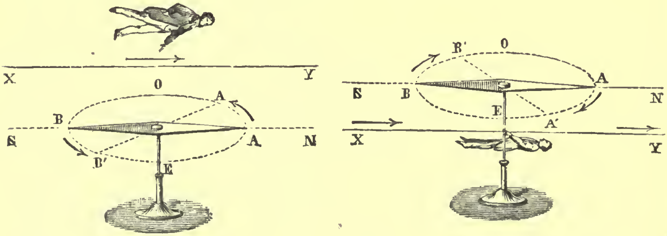

FIG. 2 *a*. FIG. 2 *b*.

Action of an electric current on a compass needle.

compass needle, as you see, immediately resumes its position from north to south. In other words, when the current is flowing in this direction the north pole of the compass needle goes to your left. That is to say, if I be looking in the direction in which the current is going, the north pole of the compass needle seems to go round the wire in the direction of the hands of a watch. And if I had the compass needle at one side of the current the north pole would still tend to turn round in the direction of the hands of a watch. The south pole tends to go in the opposite direction. Another means has been proposed for indicating the direction of motion of the compass needle. If a man be supposed to be swimming in the direction of the current and facing the compass needle, he will see the

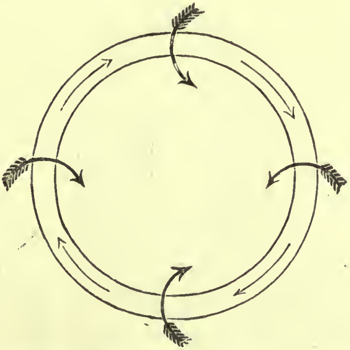

FIG. 3.—A current passing in direction of light arrows moves a north pole in direction of dark arrows.

north pole going to the left. In this way, looking at Fig. 2 *a* and Fig. 2 *b*, we see that a current going from south to north, if above the compass, deflects it to the west of north, and if below, to the east of north. There are various results which we can see to follow from this principle. Here I have a rough ring to illustrate the direction in which the current is going. (See Fig. 3.) Let the light arrows show the direction of the current. Now, I have found, when I am looking along these the north point appears to go round in the direction of the hands of a watch; so, also, looking at it from another point, the needle would still tend to go round in the direction of the hands of the watch, so that wherever in front of this circle I may hold the north pole of the compass needle it will always tend to go through the circle in that direction if the current is going in the direction of the arrows. Here, we have a method of intensifying what was shown by Oersted. If I hold a compass in front of a coil the north pole will tend to be sucked in, in that direction; and the south pole would be sucked in, in a similar manner, if held at the other side of the coil.

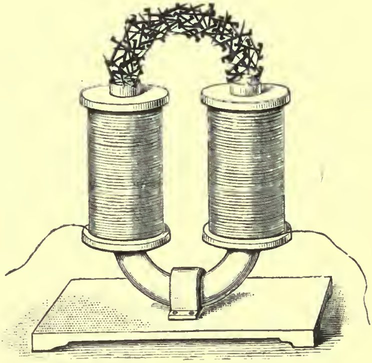

FIG. 4.—Electromagnet supporting a bridge of nails.

I will show you next another experiment to illustrate the analogy between the electric current and magnetism, which follows directly from Oersted's experiments. Here I have a mass of iron or sets of bars going directly downwards with iron at their base, and coils of copper wire surrounding them through which I can pass an electric current. As soon as I pass such a current through the wire this becomes a powerful magnet capable of attracting iron objects placed in its neighbourhood. It will hold a bar of iron like this with enormous intensity. So, if I tumble upon the poles a quantity of nails the magnetic attraction is so great as to give the nails the appearance of cohesion, which enables them to stand upright in a bridge; but as soon as I take away the current they fall down, which shows that the magnetism has left the magnet as soon as the current ceases to flow. (See fig. 4.) In this experiment the north polarity is urged through the iron in the direction indicated by Oersted's experiment.

Having shown you how a magnet can be produced, I will show you the experiment which I described just now. Here I have a coil of wire analogous to the coil which Mr. Knapp was just now holding in his hand, and here I have a bar of iron, and I have said that if I have a north pole under here it will be sucked up if the current is going in the right direction. Now the coil will magnetise this bar. As soon as I have magnetised the bar it has a north pole at the top, which is powerfully sucked in. The intensity of the magnetic effect of this current of electricity is so great that I have considerable difficulty in dealing with this mass of iron which I am holding in my hand.

Now, in this experiment I wish to point out to you the key that exists to the whole of the researches of Faraday, which were made some years afterwards. When I have this magnetic needle, which is deflected by the current, or this bar which is sucked into the coil, it is evident to every person of sense here that work is being done. That is to say, that when the needle is moved away from the position which it naturally occupies, work is being done. Where does this work come from? It comes from the interaction of the compass needle and the electric current. It is, therefore, safe to say that when a compass needle is moved in the neighbourhood of an electric current it is doing work, and in order to do work it must take away a part of the current from that current which is acting. Now, in order to take away from the current it must have tried to start a feeble opposing current in an opposite direction. And here is the point that I wish you to grasp, that in the movement of the compass needle from one side or the other, an opposing electromotive force has been created, that is, a force tending to set up a current in the wire in the opposite direction. This I believe was the manner in which Faraday argued the matter out in his mind and that is how he was able to originate the experiments which he made to produce the opposite result, that is, to create a current in the wire.

Hitherto, Oersted had shown that a current could produce motion in a magnet; Faraday conceived the idea that by the motion of the magnet we could produce a current in the wire. This experiment I shall now be able to show you. By moving a magnet pole into a coil you will be able to see a movement of the pointer which I have here, and which indicates the strength of currents which are made to flow through wires which are connected with it. This instrument which I have here is a galvanometer, an instrument whose object is to measure the strength of electric currents. You see the index travelling over the

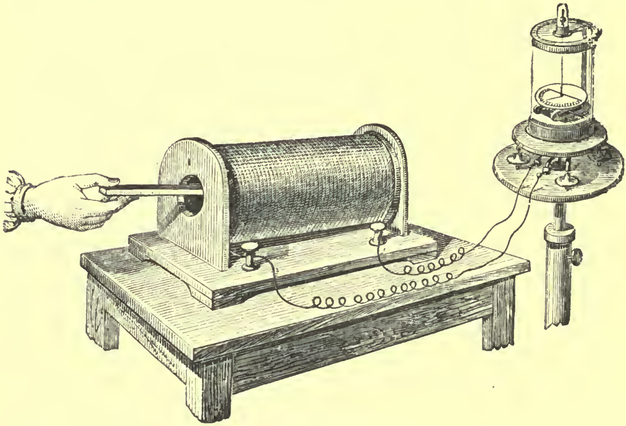

FIG. 5.—Galvanometer showing an induced current while a magnet is moving into a coil of wire.

scale at the present moment; it now points almost to the middle of the scale. If then, I take an ordinary coil of wire and reverse the experiment which I was talking of a short time ago, that is to say, pass the pole of the magnet into the coil of wire, we shall find that the electromotive force is started in the coil of wire, and if the circuit of the wire forming the coil be completed through the galvanometer, we shall find that a current is created which will show itself by the deflection of the galvanometer. (See fig. 5.) Now, in order that this be made distinct, I shall ask Mr. Knapp suddenly to insert the north pole of the magnet into the coil of wire. The movement of the galvanometer will be slight, but you will be able to see it. I will now ask him to withdraw the pole and the movement will be in the opposite direction. In this manner I get up a sort of swing in the galvanometer which is more visible to you, and shows that I can move the galvanometer needle from one side to the other when I put in the north pole of the compass or draw it out. The motion you see is slight, but I am perfectly able to control it; it moves always to the right when I put the pole in and always to the left when I take the pole out. This movement of the index proves that Faraday's notion was right.

I am anxious now to show you this experiment in another way, for it shows a further development of our notion which will enable you to understand the application of Faraday's principle to the construction of the dynamo machine, which we will be investigating in a few minutes.

Here I have a coil of wire connected up with the galvanometer. In the coil there is a bar of iron. I show you that when I magnetise the bar of iron which goes through it, there will be a deflection of the galvanometer, and when I reverse the magnetism, there will be a deflection in the opposite direction; so that when I have a piece of iron enclosed in a coil of wire all I have to do is to magnetise it by the influence of these neighbouring poles. Mr. Knapp will now magnetise the pole by touching the end with a magnet; as soon as it is magnetised there is a movement to the right. Reverse now—there is a movement to the left. This is merely an experiment which assists our comprehension of the construction of the machine, or shows that magnetising the iron core produces the same effect as the introduction of the magnetic pole into the system.

Now let us see how all these principles, discovered by Faraday, can be applied to the construction of dynamo-electrical machines. You have seen when I have a coil here with the north pole introduced through it that there is then a current of electricity established in it, and that current is established only while the north pole is passing through it. When the magnet is fixed no action is taking place. I have introduced the north pole into the coil, and if I withdraw that north pole by the way it went in, I shall of course create a current in the opposite direction. If, on the other hand, I carry the south pole in the same direction in which the north pole has gone, it also will create a current in the opposite direction. After I have passed the north pole through the coil, it is impossible to increase the current in that direction. The further motion of the other pole must produce a current in the opposite direction to the current first produced. However I may act in this way I am bound to get a motion which gives alternate currents. If I use a bar of iron surrounded by a coil of wire and magnetise it, with the north at one end and the south at the other end, I get a current; but it is impossible for me to keep that current going because I cannot get beyond a certain amount of magnetisation. If I reverse the magnetisation I produce a current in the opposite direction at the moment of reversal.

It would seem then that we have the power of producing currents alternating in direction. This was the only type of machine known for a considerable time; and all of you have seen those instruments in which a handle was turned rapidly while a person held the ends of the wire in his hand and received a succession of severe shocks; that was due to the production of alternate currents by an arrangement which alternately magnetised and demagnetised the iron core inside the coil.

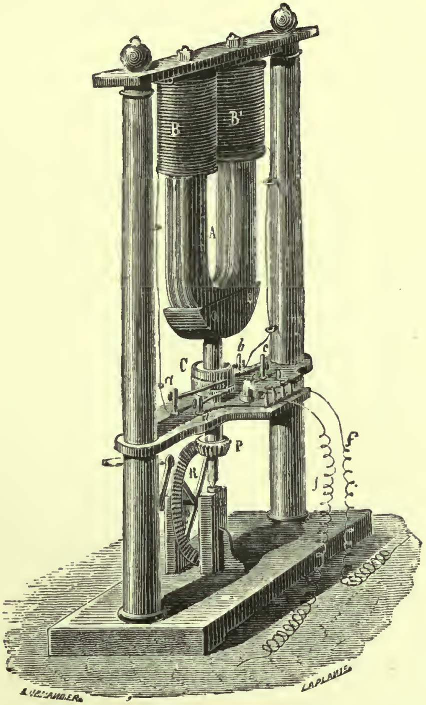

FIG. 6.—Pixii's machine.

I will now show you some illustrations on the screen which show the construction of machines for producing alternate currents in this manner.

This is one of the alternate current machines, like that of Pixii or Saxton (fig. 6). Here we have a horseshoe magnet fixed about an axis to which a rapid rotation can be given. At the top are two coils which remain fixed, and inside these coils there are bars of iron. The consequence of this is that when the magnet is rapidly rotated the north pole and the south pole will be successively presented to the coils, and the result is a continual reversal of the magnetism in those coils; and every time the magnetism is reversed a current is created in one direction or the other; and if the wires in these coils are held in the hand, a succession of violent shocks will be felt by the person holding them. One of the original machines of this type is shown in the historical collection in this exhibition.

I will put into the lantern another slide, showing a different form of machine. Here again is a horseshoe magnet. The magnet does not revolve, but the coils of wire revolve in front of the poles of the magnet. Here are the two coils at the bottom mounted upon a spindle which is horizontal. These two coils are rotated rapidly. Inside the coils are cores of iron. The cores of iron are magnetised in opposite directions as they pass from one pole of the fixed magnet to the other pole, and every time they do so, the current is changed in direction. Here also we are able to receive shocks from the coils by holding the end of the wire in the hand. In this machine, as constructed, there was an arrangement for changing the direction of the current in the outer circuit at the same time that the magnetism was changed, but of that I will speak later.

In the next slide I shall show you the most practical of all the older machines (fig. 7). This was the Alliance machine used for lighthouses in Great Britain and France. It consists of a vast number of horseshoe magnets. This machine has actually been employed in our lighthouses in

France and England. At the present moment you may see a machine made by De Meritens, which is exhibited by James W. Queen & Co., at the far end of this exhibition, and which is constructed on the same principle.

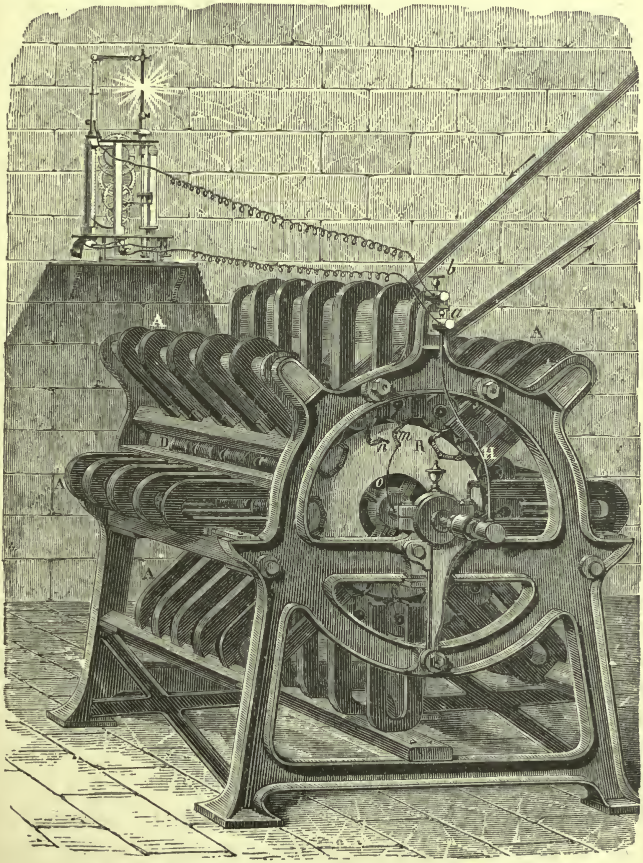

FIG. 7.—The Alliance machine for alternate currents.

A large number of rows of horseshoe magnets are about this central axis, around which also there is a ring of coils of wire each with iron enclosed, and all these coils pass in succession the poles of the magnets, and so alternate currents are created in the coils which produce a current of great intensity. These powerful currents are generated by means of a steam engine, and so we were able to get the powerful spark of the arc lamp like what was seen by Sir Humphry Davy, in 1811.

I may now pass on rapidly to the greatest improvement which was introduced, and that was the continuous current machine. It was found possible to take these currents from the machine which were alternately in opposite direction and reverse their direction through the circuit, that is to say through an arc lamp or through the hands of the person holding the wires, and thus a continuous current always in the same direction was made. A single reversal, however, did not produce a steady current and it was a long time afterwards before means were devised for creating a steady current, which was of real use in producing these continuous currents which we now use in electric lighting, and in this country in telegraphy.

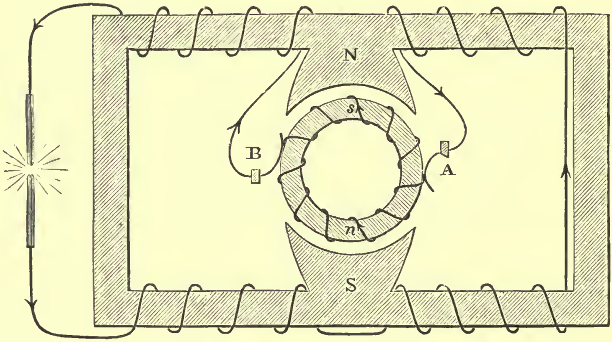

FIG. 8.—Diagram of Gramme machine (series wound), showing field magnet and pole pieces, ring armature, commutator, and direction of currents. The armature rotates with the hands of a watch.

The greatest improvement was introduced by Mr.

Gramme about the year 1870, and he did this by means of a machine, a diagram of which you can see on the wall here. This is only a rough diagram showing the principle of the machine (fig. 8).

Here is the north pole of the field magnet, marked '*N*,' and here is the south pole, marked '*S*.' These are magnetised by coils going around the mass of iron. Here is a ring of iron with coils of wire wound around it. This is the armature. The iron of the ring becomes magnetised by the influence of these north and south poles of the field magnet and the poles in the ring retain the same position in space while the ring revolves. As soon as the ring rotates it follows that these wire coils are continually passing over the pole, or I might say this pole in the iron is continually passing through the coils. In other words, an electric current is being continually developed through successive coils as they pass through here.

If you look at the sketch you will see that there is a south pole in the ring at *s* opposite to the north pole in the field magnet, and a north pole in the ring at *n* opposite to the south pole of the field magnet. If you remember the rule I have given you about the direction of currents you will be able to trace their direction in the machine. Suppose the ring to be revolving in the direction of the hands of a watch, the north pole will be going in the opposite direction through the coils, and if the eye be placed so that the north pole is coming towards it the induced current circulates with the hands of a watch; with a south pole the reverse takes place. Follow this out and you will see that the current flows in the upper semicircle from *A* through *s* to *B*, and in the lower one from *A* through *n* to *B*. But the wire is continuous, and if metallic brushes take up the current at *A* and *B* you see that the current will go out of the armature coils at *B*, through the circuit and in again at *A*.

Mr. Gramme constructed a commutator with a large number of bars to which the ends of these coils were connected, and he used metal brushes to rub on them, and thus there was a continual series of changes going on as each coil passes those brushes, and thus he was enabled to get a very continuous current of electricity through his machine.

I have put up here a small diagram to illustrate the action of these commutators (fig. 9). In the old alternate current machine there is a bobbin passing the poles of the magnet; the current increases to a maximum and falls to a minimum, then increases to a maximum in the opposite direction when there is no commutator employed (*a*). When we put in a single commutator, so as to reverse the current at each pole, it rises to a maximum and falls to a minimum, and we get this interrupted current, but always in the same direction (*b*). That was the first kind of continuous current made. Some machines were introduced to give a double commutation that is twice commutated in the course of a revolution, and thus an irregular

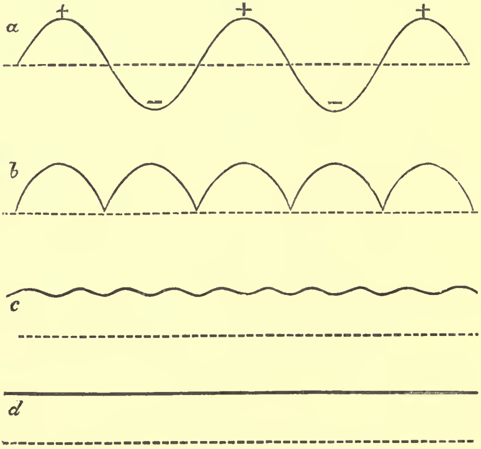

FIG. 9.—Action of commutators.

sort of current was produced (*c*); but when Gramme introduced his machine with a vast number of commutations in one revolution he had a vast number of currents, and thus there is an almost continuous current produced by the Gramme machine (*d*).

In the Gramme machine which I showed you here, the current itself is used to excite the magnetism in what are called the field magnets, and it passes through this field magnet before going to the lamp circuit. That is what is called winding the field magnets in series. Sometimes the current is taken direct from the revolving portion to the lamp circuit, and a second current is taken to the field magnets, forming two circuits, and thus the field magnets are said to be magnetised in a shunt. The practice of using the current which is induced to produce the magnetism of the field magnet was a completely new thing in 1866, and was invented simultaneously by several people, notably by Wheatstone and Siemens, who produced papers describing it on the same day in the Royal Society of London.

I will now show you on the screen a few more machines of the continuous current nature, including a Gramme machine, and some of the details of the Gramme machine, and I hope when you have seen these diagrams you will be able when going around this Exhibition to study the nature of the different machines. It is in the arrangement of the field magnet and armatures in which the machines vary. The whole evening might be given to the variations of the different machines; in the meantime I can only show you a very few illustrations of the different types of machines.

The first machine that I have to show you here is the machine of Wilde (fig. 10). Allow me to call your attention to the special parts. In the revolving armature electricity is induced. This is the seat of the electromotive force; this is the pump which pumps the water and gives it its pressure, and enables it to go through the circuit. *B B* are the magnets, which are composed of soft iron, magnetised by the coils of wire surrounding them. In Wilde's machine he had a small machine, *P*, with permanent steel magnets, fixed on top of the larger

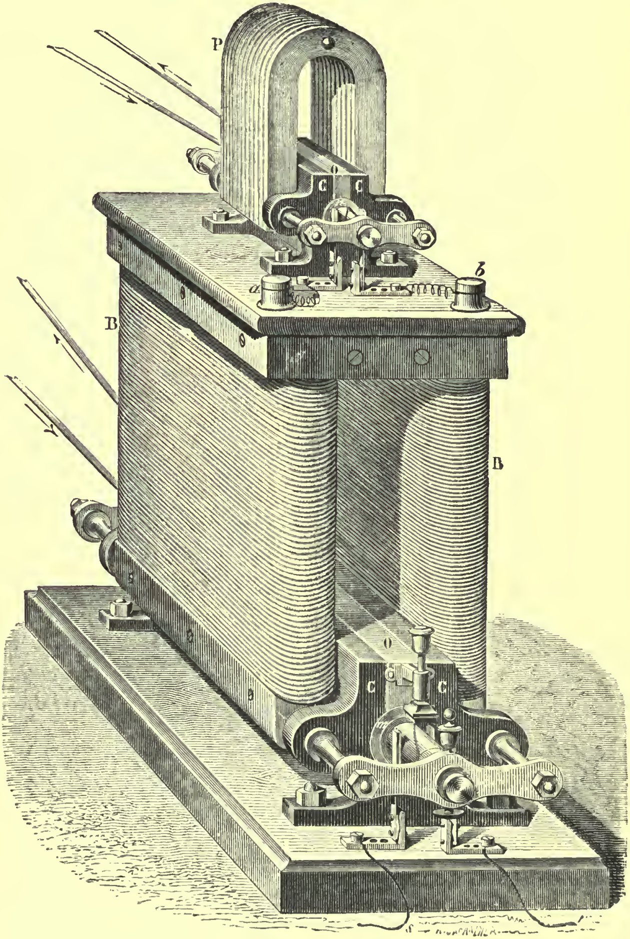

FIG. 10.—Wilde's magneto-electric machine.

one. They are not so powerful magnets as these electromagnets, and he used to induce a small current of electricity instead of using the larger current to magnetise these electromagnets. It created a feeble current, which circulated around these field magnets, and gave an intense magnetism to these pole pieces *C C*. These pole pieces being polarised, and the armature revolving, the coils of the armature developed an electric current of great intensity, far surpassing the current developed by the little machine. Thus he was enabled to get a very great current, sufficient for electric lighting.

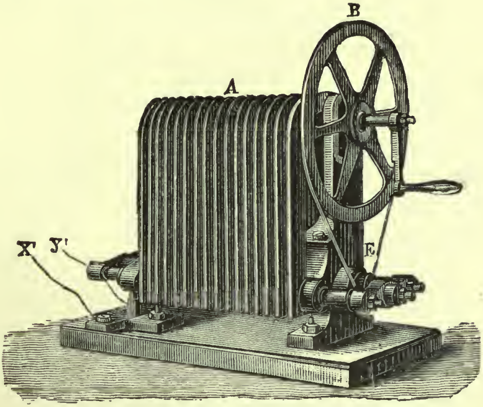

FIG. 11.—Siemens' machine.

This next slide is a Siemens' machine, made also with permanent horse-shoe magnets (fig. 11). You will see the revolving part attached to the driving gear at *E*. That revolving part is of course the armature; the coils of the armature being between the pole pieces. This central part is a mass of iron, and the coils of wire run longitudinally around the core (fig. 12). This machine, as originally constructed, had simply a single commutator, which reversed the current once in each revolution, which sent a continuous but varying current through the circuit.

This slide (fig. 12) is a Gramme machine, and was introduced to the public shortly after 1870, and this machine has been the basis of nearly all the dynamo machines seen in the world. These round parts at the bottom and top, surrounded by coils of wire, and the pole pieces seen at the top and bottom, are the magnets. There is the Gramme armature, which rotates about the horizontal axis, and here is the commutator.

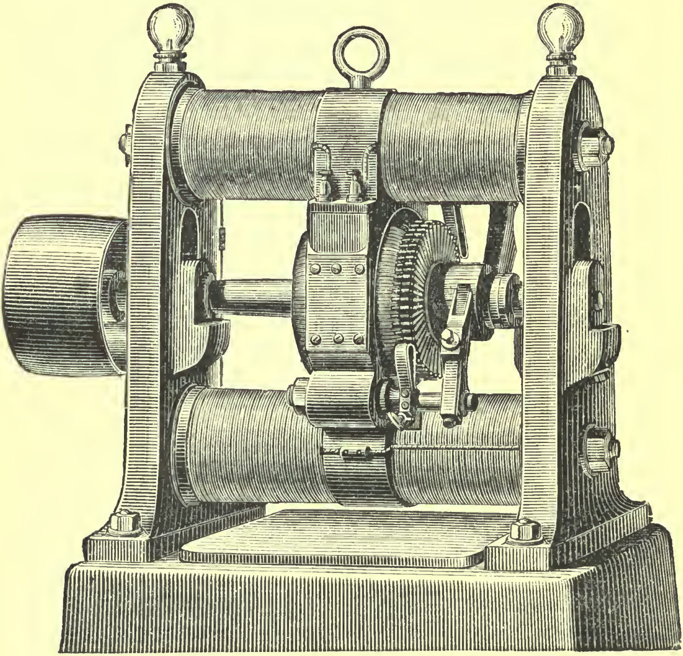

FIG. 12.—A Gramme machine.

This next picture is an ideal Gramme ring (fig. 13). Here are the successive coils. Here is the south and here is the north pole of the ring. You will notice that in each coil, as it passes the pole, an electric current is developed.

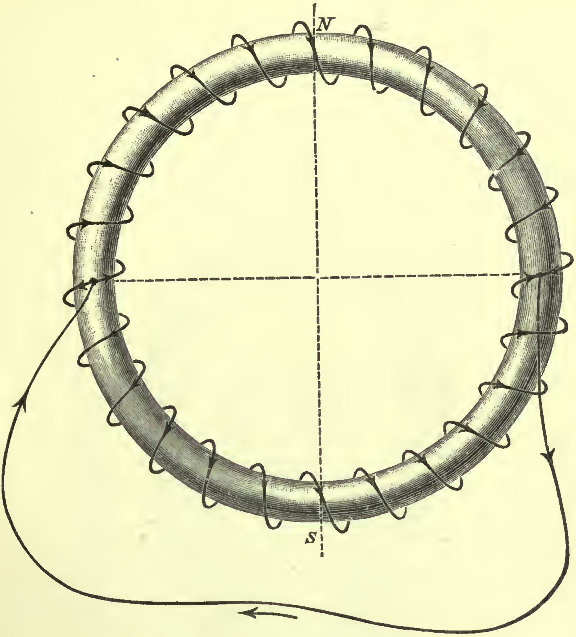

FIG. 13.—Ideal Gramme ring.

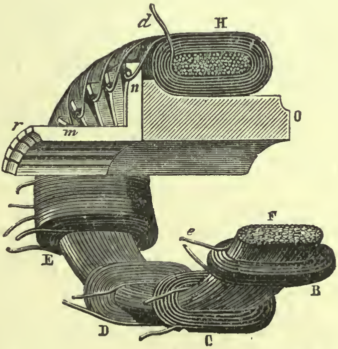

FIG. 14.—Portion of a Gramme ring, showing the mode of construction.

F is a section of the iron ring made up of iron wire. B is a coil with the wire ends ready for attachment to commutator bars.

The current will always be in the same direction, at any part of the ring, and very nearly continuous.

The next picture is a portion of a Gramme ring (fig. 14). It shows the way it is made up; it consists of a central core of iron wire and coils of insulated wire successively laid upon it. It is cut, showing the ends of the wires projecting.

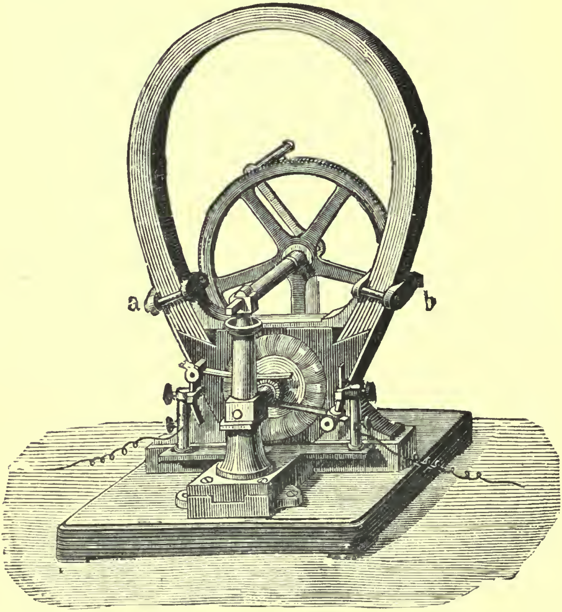

FIG. 15.—Hand Gramme machine.

Here is a small Gramme machine, which can be worked by hand (fig. 15). In construction it is exactly similar. Here are the poles; there is a revolving ring; the commutator is on the other side, and cannot be seen.

This picture is of a machine of very remarkable historical interest (fig. 16). This was designed by Pacinotti, and described about the year 1864. It is exactly like a Gramme ring in many points. It revolves around a vertical axis instead of a horizontal axis, and as it revolves the current is picked up by a commutator. This was made on a small scale, and was not used for commercial purposes. It is conclusively proved, however, that Gramme did not know of the work of Pacinotti, but it is incontestable that Pacinotti was the inventor of the type from which all the other machines have been constructed.

An attempt has been made to improve the constancy of the current, and prevent the difference in intensity which is observed when we are using a large or small number of lights. It is found with some kinds of machines that the intensity of the electromotive force increases when we add lamps to the circuit, and in other kinds we find the opposite is the case. When the field magnet of a machine is wound as a shunt, as we diminish the number of lamps, the lamps left burning increase in brightness. The machine which illuminates this hall is one with a shunt. It is the large Edison machine. This machine will not show the effect very much, because the armature of that machine is

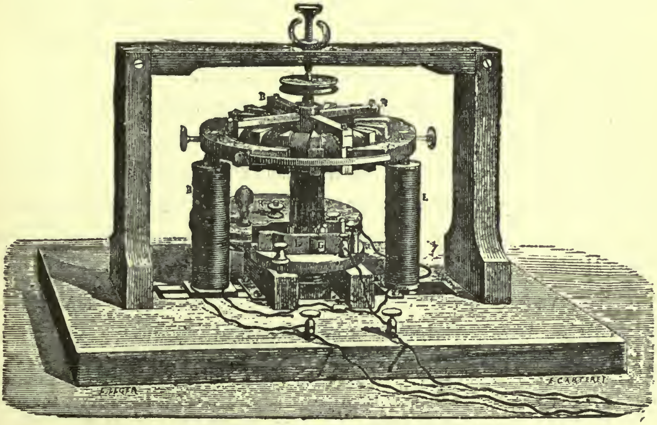

FIG. 16.—Pacinotti's machine.

made of very low resistance, and it is only lighting 300 lamps instead of 1,500; and the electromotive force or pressure is steady, however we vary the number of lamps. Still it is a shunt-wound machine, and there is a slight difference between the intensity of the lights.

I will now put out the lights in succession, and leave these two lamps to be last put out. You will notice that there is a slight increase in the brightness of the last two lights; it remains with you to notice that the change is very slight indeed. This illustrates how we can make a machine that will regulate itself; that is, however many lamps we put upon the circuit the electrical pressure is the same and the intensity remains constant.

Now watch these two lights as the others are put out in succession. You see they are decidedly getting brighter. Put them in again and you will see the opposite effect take place. You will see them dimming. Now, this is distinctly dimmer than it was a little while ago, though but very little. It is quite evident to you that a machine like the Edison (the machine producing these lights is what is called the Jumbo) does not vary much when we vary the number of lamps up to 300. It is astonishing when we descend to one lamp and show such a small variation in the light. In an ordinary small machine the change of brightness would have been decided. In the shunt-wound machine, when we increase the number of lights we diminish the intensity of each. In the series machine the opposite is the fact. I might show you that experiment, but time is passing quickly. That is to say, when we put in one lamp in a series machine it hardly glows at all. The reason is that the current is very feeble with one lamp, because the resistance in the circuit is very great. When the current is feeble the magnetism of the field magnets is feeble, and that is the cause of the low electromotive force. As I increase the number of lamps I am increasing the means of escape; that is, I am increasing the number of pipes of my hydraulic system, and letting more water flow, and the magnetisation is more complete.

Of late years it has been attempted to produce perfect equality even in the small machines, and without going to the vast dimensions of the large-size Edison machines, by winding the field magnet in a double way, partly as series machine and partly as shunt machine. I have already explained to you that when we have a shunt-wound machine the electromotive force gradually diminishes as we put in more lamps; and I have shown that in the series machine the electromotive force gradually increases as we reduce the resistance and put in more lamps. Therefore, taking the mean of these, or summing these two together by winding these two magnets partly in series and partly in shunt, the electromotive force does not vary in so great a degree. Thus we are able to get by a proper adjustment a perfect equality or difference of potential between the two parts of the line, and, whether we are dealing with the terminals, at the machine itself, or where the lamps are applied a mile away, by a proper compound winding, partly in series and partly in shunt, we are able to produce a compound machine which gives a constant electromotive force however many lamps we are using—that is, however many pipes we may have drawing off water from our supply.

I had hoped to have spoken about the effects of alternate current machines, which would have been extremely interesting; but time is passing so rapidly that it is impossible to deal with this subject now. I will only show you one remarkable experiment by means of the alternate current passed through a coil of wire on one arm of the electromagnet and through an incandescent lamp.

I will show these effects, because they are very remarkable. The effects of the alternate current machines are difficult to understand at first sight. Perhaps, if I explain to you this one action I may have given some information to some of my audience here, and it may enable them to see some of the difficulties to be met with in alternate current machines, and enable them to avoid making mistakes in their applications in the future. I will pass an alternate current through one coil of the electro-magnet, and also through one incandescent lamp. That lamp glows very feebly indeed. But as soon as I join the terminals of this wire, going round the second coil of the electro-magnet, it immediately glows brightly. See fig. 17.

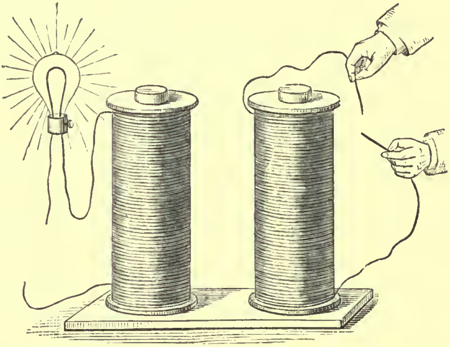

FIG. 17.—An alternate current passing through one arm of an electro-magnet and an incandescent lamp. When the ends of the other coil are separated the lamp is dull; when joined the lamp is bright.

When I have an alternate current passing through this first core, it is exercising a large power in magnetising and demagnetising that core. That core exercises its influence upon the other core to magnetise and demagnetise it. Thus the iron in these two arms of the magnet is being magnetised and demagnetised with great rapidity, and it is taking away from the current which is feeding this lamp. But so soon as I connect the wires of this other coil I am using up the power and magnetism in this core. I am making it do work in creating currents in this second coil; that is to say, this second coil acts as a drag on the magnetism of the core. So soon, then, as I connect the ends of the wire of this second coil the magnetism cannot change there so suddenly, and the primary current is not able to do so much work in the magnet, and therefore it is more free to exert its own force, and therefore it enables the lamp to glow with greater brightness than it did before.

I must not trespass upon your time longer; I feel that I have already exhausted the limits which I had set myself, and which ought to be set to a lecture of this kind. On the subject of dynamo-electric machines several lectures might advantageously be given. We have, I think, advanced a great distance in the way of theoretical application of the laws of electricity to the dynamo-electric machines; we owe a great deal of this not only to the advance in theory but also to the advance in the application of theory. There is a great deal still to be done by theory and by practical application. If we look to the past we shall find that there has been too much hesitation on the part of practical men in accepting the results of theory; and if we look with hope to the future we shall see theoretical views put to practice to guide us and direct us in our efforts to arrive at perfection.

On a recent occasion Lord Rayleigh, the president of the British Association, at Montreal, and also the very distinguished professor at the University of Cambridge, England, stated that he was astonished to find, considering how well known were the laws of induction in the time of Faraday, and how complete was our knowledge of electrical induction in those years long past—he was astonished to find at how slow a rate the practical applications of those principles long ago published by Faraday had been introduced into every-day work. Lord Rayleigh then stated his opinion that the cause of this slowness to apply the achievements of science was due to want of faith, and I agree with him that this is the true solution of the enigma. Faraday was a man whose mind was taken up with original investigation. Faraday had as complete a mathematical conception of the theory of electricity as any of us who have studied Clerk Maxwell's book could have, although he could not express one word of his ideas in terms of x, y and z. And in this way from the experiment of Oersted he was able to divine in his own mind the consequences of that experiment, and foresee the results of his own experiments in developing electromagnetic induction; whereas you would have thought it was only by the application of the higher mathematics that this could have been done. He also had this peculiarity—that he knew what his bent was, and in what manner he could be of the most benefit to mankind. He says himself, in one of his writings, as much as this. In speaking of the possible applications, and throwing out a hint as to the manner in which powerful dynamo-electric currents might be created, he makes use of the following language: 'But in all my work it has been my endeavour not to seek out applications in practice so much as to arrive at new principles.' I speak from memory, but I think these are nearly the words that appear in his 'Researches.' This was the key to his life. He knew that he had an inherent power to discover new principles, and that if he left the applications to others they would come in time.

In this past history of the applications of electricity we have thus to remember that thirty, forty, and even fifty years ago we had the knowledge which was given us by Faraday, which would have enabled us to construct this dynamo-electric machine, and it was only through want of faith in those whose duty it is to deal with the applications of scientific facts that the slowness has been due. And in future let it be hoped that theory and application will work hand in hand, and that, while theorists see that the value of their investigations and the impetus which prompts them are due to their practical application, so others whose duty it is to apply science commercially may see that the rapidity of these applications depends upon the acceptance of the results of theory; and if this Exhibition and this course of lectures lead those who apply science to study a little more fully the new ideas which theory is teaching us, and if they lead theorists to see a wider range for the applications of theory, then the managers of this Institute will have had the best reward possible for giving these lectures in knowing that they have been of some avail.

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